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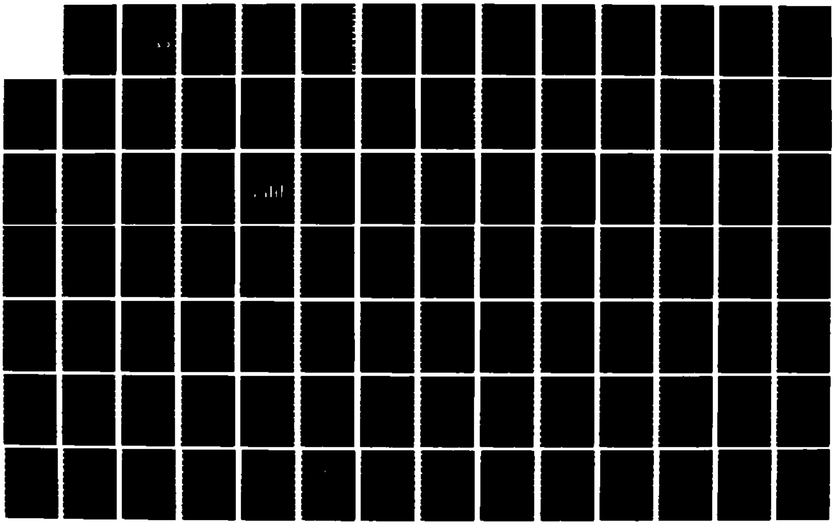

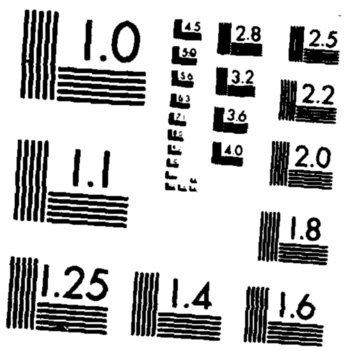

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ASSESSING THE BENEFITS AND COSTS OF MOTION FOR C-17 FLIGHT SIMULATORS: TECHNICAL APPENDIXES

J. R. Gebman, W. L. St , . A. Barbour,
R. T. Berg, J. L. Birk . G. Chaloupka,
B. F. Goeller, L. M. J , R. J. Kaplan,
T. F. Kirkwood, with C. L. Batten

June 1986

RAND

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(Rand report)

This document provides technical support for R-3276-AF. Appendixes describe (1) experiments to determine the value of motion in training simulators; (2) aircraft features that will influence the motion of the C-17; (3) possible effects on motion cues of the C-17's stability and control augmentation system; (4) the fidelity of different simulator motion cueing alternatives; (5) a suggested methodology for assessing the training capability of simulators; (6) the effects of simulator motion on simulator training capability, safety, and avoidance of simulator sickness; and (7) the costs of providing motion in simulators.

A RAND NOTE

N-2301-AF

ASSESSING THE BENEFITS AND COSTS OF MOTION FOR C-17 FLIGHT SIMULATORS: TECHNICAL APPENDIXES

J. R. Gebman, W. L. Stanley, A. A. Barbour, R. T. Berg, J. L. Birkler, M. G. Chaloupka, B. F. Goeller, L. M. Jamison, R. J. Kaplan, T. F. Kirkwood, with C. L. Batten

June 1986

Prepared for

The United States Air Force

RAND

PREFACE

In November 1984, the U.S. Air Force Deputy Chief of Staff for Research, Development, and Acquisition, Lieutenant General Robert Russ,[1] asked The Rand Corporation to perform a quick assessment that would assist the Air Force in evaluating the benefits and costs of incorporating motion systems in C-17 transport aircraft flight simulators and in developing a general framework for assessing simulator fidelity requirements. The results of this assessment were briefed to Air Force leadership early in the spring of 1985.

This volume contains technical appendixes that support findings detailed in *Assessing the Benefits and Costs of Motion for C-17 Flight Simulators*, by J. R. Gebman, W. L. Stanley, A. A. Barbour, R. T. Berg, J. L. Birkler, M. G. Chaloupka, B. F. Goeller, L. M. Jamison, R. J. Kaplan, T. F. Kirkwood, with C. L. Batten, The Rand Corporation, R-3276-AF, June 1986.

This research was conducted as a direct assistance activity by the Project AIR FORCE Resource Management Program.

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[1]Lieutenant General Russ was subsequently promoted to General and is now Commander, Tactical Air Command.

ACKNOWLEDGMENTS

The authors acknowledge the assistance of many elements of the U.S. Air Force, including Headquarters Military Airlift Command, the 314th Tactical Airlift Wing at Little Rock Air Force Base, Headquarters Strategic Air Command, the KC-10 Aircrew Training component of 4235 Strategic Training Squadron at Carswell Air Force Base, the 2d Strategic Bomb Wing at Barksdale Air Force Base, Headquarters Air Training Command, the Aeronautical Systems Division (ASD) C-17 System Program Office, the ASD Simulator System Program Office, the ASD Office of the Comptroller, the Ogden Air Logistics Center, the Human Resources Laboratory Operations Training Division, the Aerospace Medical Research Laboratory, and the Air Force Operational Test and Evaluation Center.

They also acknowledge the assistance of the U.S. Navy provided by the Naval Training Equipment Center and the VP-31 P-3 Training Replacement Squadron.

Other assisting government organizations include the National Aeronautics and Space Administration (NASA) Langley Research Center, the NASA Ames Research Center, Headquarters Federal Aviation Administration (FAA), and the Office of the Manager of the FAA National Simulator Evaluation Program.

Assisting private organizations include the Massachusetts Institute of Technology Department of Aeronautics and Astronautics, the American Airlines Training Corporation, the American Airlines KC-10 Training Center at Barksdale Air Force Base, the United Airlines Aircrew Training Corporation, the Seville Training Systems Corporation, the Allen Corporation, the Boeing Commercial Airplane Company, the Boeing Military Aircraft Company, the General Electric Company Simulation and Control System Department, the Lockheed-Georgia Company, the Douglas Aircraft Company, the Reflectone Corporation, and the Singer Company, Link Flight Simulation Division.

The authors also acknowledge the guidance and assistance provided by the research sponsor through General Robert Russ and Lieutenant Colonel Eugene Clayton.

Finally, the authors particularly acknowledge the assistance of Colonel David Nelson and Lieutenant Colonel Ronald Duke at Headquarters Military Airlift Command, and of Rand colleagues P. Perkins, who compiled the bibliography, B. D. Bradley, S. M. Drezner, G. H. Fisher, M. D. Rich, J. A. Thomson, and W. H. Ware, who provided suggestions and comments in the course of this research, and E. D. Harris and S. Resetar, who provided perceptive technical reviews.

ABBREVIATIONS AND ACRONYMS

ACM	Air Combat Maneuvering
AFB	Air Force Base
AFHRL	Air Force Human Resources Laboratory
AGL	Above Ground Level
ALC	Air Logistics Center
ALCOGS	Advanced Low-Cost G-Cueing System
AMST	Advanced Medium STOL Transport
AS(U)PT	Advanced Simulator for (Undergraduate) Pilot Training
cg	Center of gravity
CGI	Computer Generated Imagery
CONUS	Continental United States
CRT	Cathode Ray Tube
DLC	Direct Lift Control
dof	Degrees of freedom
FOL	Forward Operating Location
FOV	Field of View
FSD	Full Scale Development
HUD	Heads-Up Display
ILS	Instrument Landing System
JAATT	Joint Airborne and Air Transportability Training
KIAS	Knots Indicated Air Speed
LAPES	Low-Altitude Parachute Extraction System
LCC	Life-Cycle Costs
MAC	Military Airlift Command
O&S	Operations and Support
ORI	Operational Readiness Inspection
SAAC	Simulator for Air-to-Air Combat
SAAF	Small Austere Air Field
SCAS	Stability and Control Augmentation System
Sim SPO	Simulator System Program Office
SIMCERT	Simulator Certification
STOL	Short Takeoff and Landing

UPT	Undergraduate Pilot Training
VSTOL	Vertical Short Takeoff and Landing
WBS	Work Breakdown Structure
WST	Weapon System Trainer

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FIGURES

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INTRODUCTION

by
J. R. Gebman

The use of modern flight simulators has grown dramatically during the past 15 years motivated by the increased costs of operating aircraft and by a recognition that simulators contribute to safety and training efficiency. Simulators have incorporated greater and greater levels of fidelity to provide more realistic training. For example, motion platforms for flight simulators now have more degrees of freedom, and their visual displays now have wider fields of view and greater scene content. Depending on the sophistication of a simulator, an air transport pilot can now satisfy total recurrent training requirements, upgrade from copilot to captain status, transition from one airplane to another in the same group, and even receive total initial training and a rating for a new aircraft, entirely through use of the simulator and thus without having to use the aircraft for any dedicated training flights.

Increased realism in simulators has usually been equated with improved training, and lower costs of simulator time versus aircraft time have historically muted debate about the additional costs of increased realism. Now, however, simulation technology--particularly technology associated with visual displays--has progressed to such an extent that users are beginning to question how much fidelity is enough.

Lacking a formal framework for evaluating requirements for various simulator features, the Air Force has occasionally expressed concern that it may be purchasing unneeded simulator features. Most recently, it has raised questions about the need for a motion system in the C-17 transport simulator. To help answer these questions, the Air Force requested The Rand Corporation to examine the benefits and costs of incorporating a motion system in the C-17 simulator, and to suggest a more general framework for assessing simulator fidelity requirements in general, and motion cueing alternatives in particular.

A companion document[1] states our findings: If the Air Force devises an adequate training syllabus for C-17 simulators, and if adequate aircraft performance data are collected during flight testing to support simulator software development, then a six-degree-of-freedom (dof) motion platform will improve flight safety and increase war fighting capabilities. Moreover, the motion platform alternative, with its greater cueing capability, will provide more protection against unknown risks caused by omitting motion cues during training, especially for young and inexperienced aircrews. The costs of motion platforms appear warranted when measured against these likely benefits. In contrast, simulators with no motion systems or those using combined hydraulic/pneumatic g-seats do not appear to be cost-effective alternatives for the C-17 training application.

This Note contains technical appendixes that support our findings. Appendixes A through E serve as an *introduction* to our study:

- Appendix A describes experiments that have attempted to determine the value of motion in simulators.
- Appendix B describes C-17 aircraft features that will influence the character of its motion.
- Appendix C assesses how the C-17's stability and control augmentation system (SCAS) could affect motion cues.
- Appendix D evaluates the cueing fidelity of different simulator motion alternatives.
- Appendix E describes the methodology we used to assess the training capability of differing kinds of simulators.

Appendixes F, G, and H detail the *benefits* of providing motion in simulators:

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[1] J. R. Gebman, W. L. Stanley, A. A. Barbour, R. T. Berg, J. L. Birkler, M. G. Chaloupka, B. F. Goeller, L. M. Jamison, R. J. Kaplan, T. F. Kirkwood, with C. L. Batten, *Assessing Benefits and Costs of Motion for C-17 Simulators*, The Rand Corporation, R-3276-AF, June 1986.

- Appendix F examines the effects of simulator motion on simulator training capability.
- Appendix G examines the effects of simulator motion on safety.
- Appendix H examines the effects of simulator motion on avoiding simulator sickness.

Finally, Appendix I details the fiscal *costs* of providing motion in simulators. The Bibliography lists all works examined in the course of this study.

Appendix A

EXPERIMENTS INVOLVING THE VALUE OF MOTION IN SIMULATORS

by

T. F. Kirkwood and R. T. Berg

Our study of experiments involving the value of motion in simulators consists of two parts: a survey of the literature and a description of several motion tests performed for us at Little Rock Air Force Base (AFB). The experiments at Little Rock were neither extensive enough nor carefully enough controlled to allow conclusions to be drawn from them. They were, however, invaluable in revealing the problems of undertaking valid experiments with simulator motion and in drawing meaningful conclusions from them.

SURVEY OF THE LITERATURE

Our literature survey was primarily concerned with experiments that were most directly applicable to the issue of motion for the C-17 simulator. This meant that we focused on experiments dealing with transport-class aircraft using non-centerline thrust and with tasks that would be encountered in transport aircraft flight. However, we also examined experiments involving air-to-air combat, helicopter operations, and fighter aircraft using centerline thrust. In addition, some of the simulators used in the older experiments had large time-lags in the motion system (Seevers, 1979), limited range of motion, and abrupt motion washout. These shortcomings have all been avoided in more recent simulators, and this raises a question as to the validity of these earlier tests. We examined both the early and the recent tests, and, so far as we could tell, they seemed to lead to the same general conclusions.

Experimental results are often difficult to interpret because of the large number of variables involved (see Table A.1). Changes in any of these variables might affect the difference between motion and no-motion operation. Faced with this large number of variables, experimenters have resorted to experiments that attempt either to reach "general" conclusions or to answer a specific question in a specific conte^t.

Table A.1

VARIABLES THAT MAY AFFECT THE OUTCOMES OF MOTION EXPERIMENTS

PILOTS	AIRCRAFT
Experience	Performance
Flight hours	Stability
Simulator hours	Structural flexibility
Instructor hours	Flight control system
Background	Size
Fighters	
Transports	SIMULATOR DESIGN
	Degrees of freedom (fixed to six-dof), size, and platform dynamics
TASKS	Seat shaker, g-seat
Routine	Visual display characteristics
Emergency	Platform drive algorithms
Combat	Aircraft data base
Weapon delivery	
Payload delivery	SIMULATOR ROLE IN OVERALL TRAINING
Air drop	Cockpit procedures
LAPES	Weapon system trainer
	Training hours in aircraft

Finally, many experiments investigate the effect of motion in the simulator, but do not examine whether training in the simulator transfers to operation in an actual aircraft. Interpretation of tests that do not include transfer of training is uncertain, and understanding of the transfer of training process is very limited.

With these difficulties in mind, we reviewed the literature on the effect of platform motion in training, and reached the following conclusions:

- *Experimental data on the effect of motion on pilot performance are mixed.* In some tests, motion results in modest improvements, but motion has never been shown to result in a strong improvement. On the other hand, it has not been shown to be a detriment.[1]
- *Performance gains due to motion have not always transferred to the aircraft, and pilots trained without motion often adapted quickly to the actual aircraft and performed as well as those trained with motion* (Koonce, 1974, 1979; E. L. Martin, 1981; Ryan et al., 1978). Pilots appear to accept and react to motion with very little training. While some data (Williges and Roscoe, 1973) suggest that inappropriate motion is worse than no motion, other data show that pilots trained without motion adapt to the presence of motion quickly (Parris and Cook, 1978), and one source (Beck, 1974) indicates that pilots adjust quickly even to spurious motion.
- *Experiments have not been able to demonstrate a strong effect of simulator design (degrees of freedom, length of stroke, or the use of g-seats) on pilot performance.* One experiment (Parris and Cook, 1978) indicated that increasing the length of stroke of the motion cylinder resulted in some improvement in task performance. G-seats, g-suits, and motion (at least in their present state of development) appear to be less important

[1]Ashworth et al., 1984; Bray, 1973; Cyrus, 1978; Douvillier and Turner, 1960; *Flight Simulators: Hearing before the Subcommittee on Research & Development of the Committee on Armed Services*, 1976; Gray and Fuller, 1977; Gressang, 1976; Hosman and Vandervaart, 1981; Ince et al., 1975; Irish and Brown, 1978; Irish and Buckland, 1979; J. J. Adams et al., 1971; Klier and Gage, 1970; Koonce, 1974; Koonce, 1979; Leibowitz et al., 1982; E. L. Martin, 1981; Matheny et al., 1984; Nataupsky et al., 1979; Parris and Cook, 1978; Parrish and Martin, 1975; *Piloted Aircraft Environment Simulation Techniques 1978*, 1978; Pohlmann and Reed, 1978; Ricard and Parrish, 1984; Rolfe et al., 1970; Ryan et al., 1978; Showalter and Parris, 1980; van Gool, 1978b. These references include experiments on both old and new simulators, on tasks required by transport aircraft as well as air-to-air combat, and on centerline thrust and multi-engined aircraft. Nevertheless, our conclusion as to the small effect of motion on task performance seems to hold regardless of these considerations.

in task performance than pilot experience, as in simulated air-to-air combat (Irish and Brown, 1978; Irish and Buckland, 1979). In cases in which motion is beneficial, it is not always necessary to supply full-scale motion cues (J. J. Adams et al., 1971).

- *Although some pilots find motion distracting, most pilots and instructors express a strong subjective preference for motion.* But the degrees of freedom or length of stroke necessary to satisfy them is not clear. While not a direct measure of task performance, pilot confidence in the simulator and in its representation of the aircraft may be of great importance. To produce a good pilot, it is necessary not only to teach him the needed skills, but also to convince him that he has these skills and can employ them when necessary. When asked in one study (Beck, 1974) why they preferred motion, pilots said it

  -- Affords beneficial cues
  -- Facilitates tasks and vehicle stabilization
  -- Focuses attention
  -- Increases realism
  -- Reduces expenditure of effort
  -- Keeps them from overcontrolling

In addition, our review of the literature uncovered three recurring findings that illustrate the influence of motion on important aspects of pilot behavior:

1. *Control movements are more similar to those in the real aircraft when motion is used in the simulator* (Matheny et al., 1984; Parris and Cook, 1978; Rolfe et al., 1970). Unrealistic control movements are one of the biggest objections to simulators without motion, and they probably account for an increase in effort reported by pilots when no motion is used (Hofman, 1976; Koonce, 1974; van Gool, 1978a).
2. *Acceleration onset cues may be sensed prior to the corresponding visual cues.* Experiments on modeling the pilot's control movements have indicated that motion reduced the extent of his low-frequency control movements and also reduced the

time-lag before the control movement was initiated (*Piloted Aircraft Environment Simulation Techniques*, 1978). However, other tests in which the time-lag was measured directly show little effect of motion (Parris and Cook, 1978).

3. *In the absence of motion, pilots have been observed to alter their instrument cross-check*. While the effect this has on task performance or transfer of training is uncertain, it clearly demonstrates that the presence of motion affects the way in which the pilot flies (Comstock, 1984; Spady and Harris, 1983; Spady et al., n.d.).

LITTLE ROCK MOTION TESTS

A series of tests on the effect of motion were run in the Little Rock C-130 weapon system trainer (WST) simulator by the C-130 simulator certification (SIMCERT) team to aid our investigation.[2] These tests were not, and were not intended to be, sufficiently extensive or well controlled to allow definitive conclusions to be drawn. Rather, they served to initiate the Rand team into the problems of making and interpreting such tests, to demonstrate the Little Rock capability to run such tests, and to provide a preliminary (although not definitive) feel for the effect of motion on pilots of different skill levels.

For this reason, the test program was exploratory in nature and aimed at breadth rather than depth, both in the choice of maneuvers (selected as likely to provide important motion cues) and pilots (selected to represent a wide range of experience). With such a broad range of maneuvers and pilots, it was not possible to make enough tests to obtain statistically significant results. Thus the results we show here should be regarded as exploratory only.

---

[2]The C-130 WST has a modern six-dof synergistic motion platform and a five-window, four-channel, day-night-dusk cathode ray tube visual display system.

Table A.2

PILOT EXPERIENCE FOR LITTLE ROCK TESTS

Pilot	C-130 Flying Hours	Total Flying Hours
Copilot #1	0	300
Copilot #2	0	300
Copilot #3	600	800
Aircraft Commander #1	0	1,200
Aircraft Commander #2	0	1,200
Instructor #1	1,800	2,000
Instructor #2	3,400	3,600
Instructor #3	2,700	2,900
Instructor #4	2,300	2,500

The tests required 12.5 hours of simulator time and involved nine pilots. Table A.2 summarizes their flying experience.

Four maneuvers were tested:

- #1 engine failure at rotation during takeoff--takeoff continued
- #1 engine failure during takeoff at 105 knots indicated air speed (KIAS)--takeoff aborted
- #1 engine failure at 200 ft above ground level (AGL) during instrument landing system (ILS) approach--engine out landing
- Low-altitude parachute extraction system (LAPES) airdrop.[3]

A crosswind and air turbulence were included in all cases. Pilots performed each maneuver four to six times, half with motion, half without. Additional maneuvers were performed as distractions and were not measured. Transfer of training was not investigated. Records of airspeed, altitude, sideslip, pitch, and all control positions were produced on hard copy, and additional data were stored on tapes.

[3]At an altitude of about ten feet, the load is pulled down the cargo ramp and out the rear of the aircraft by deploying a parachute. This is a very demanding maneuver because of the low altitude and large center of gravity excursions caused by the moving load.

In reducing these data, we were concerned with any indications that motion affects

- The way pilots fly airplanes
- The safety of maneuvers.

Effect of Motion on How Pilots Fly Airplanes

We obtained a first impression of the effect of motion by comparing the time histories of altitude, sideslip angle, and pitch angle in flight after an engine failure on takeoff. Figure A.1 shows comparisons for Instructor #2, and Fig. A.2 shows comparisons for Copilot #1 (both shown in Table A.2). It should be remembered that these comparisons are between particular cases; we have no idea how representative they may

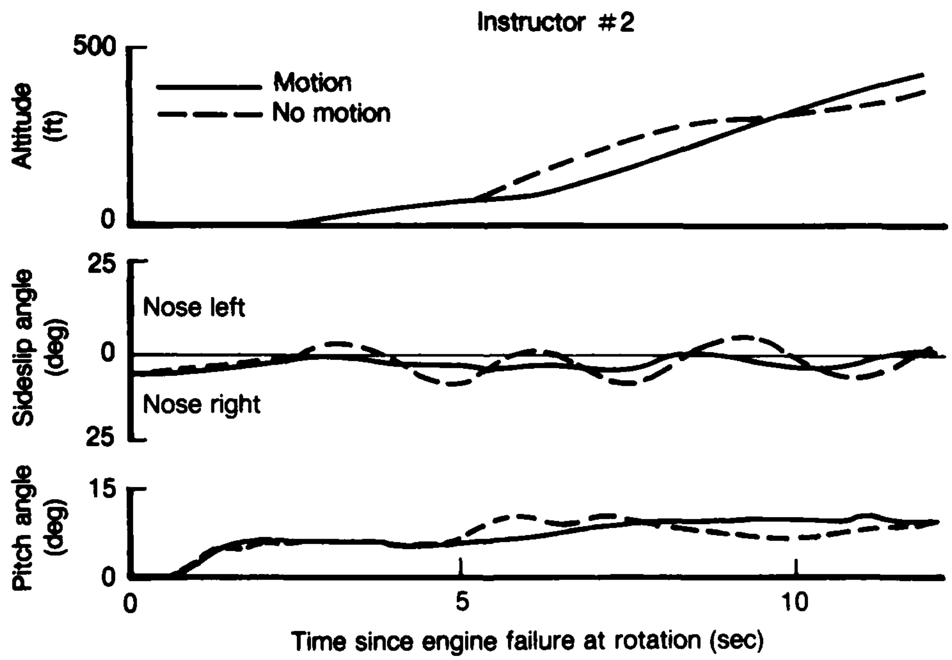


Fig. A.1 -- Effect of simulator motion on instructor (takeoff after an engine failure at rotation)

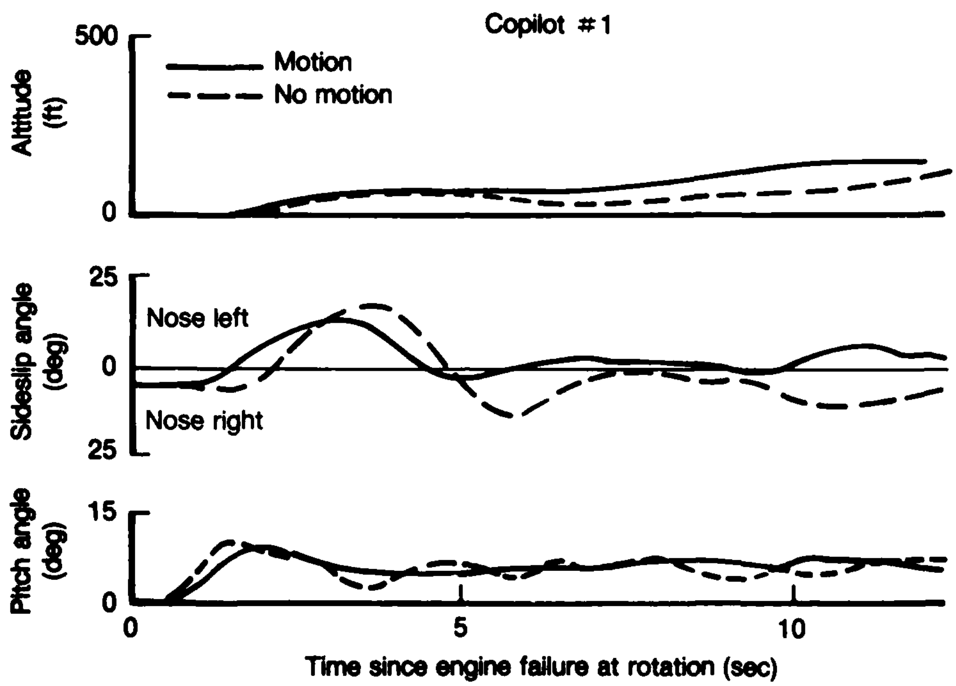


Fig. A.2 -- Effect of simulator motion on copilot
(takeoff after an engine failure at rotation)

be. Furthermore, we note that the copilot had no previous flying hours in a C-130 and consequently was contending with an unfamiliar airplane as well as with the problems of motion and no motion.

Although the instructor's performance is much smoother than the copilot's and results in a much more rapid gain of altitude, both instructor and copilot show a tendency to overcontrol when motion is absent. This is true in altitude, sideslip, and pitch.

We made a similar comparison on the LAPES delivery, although in this case we had data only on an experienced LAPES-qualified instructor (Instructor #4 shown in Table A.2). In spite of this experience, however, Fig. A.3 indicates that the change in pitch angle in the pushover used to counter the pitch up after the drop is almost twice as great without motion as with it.

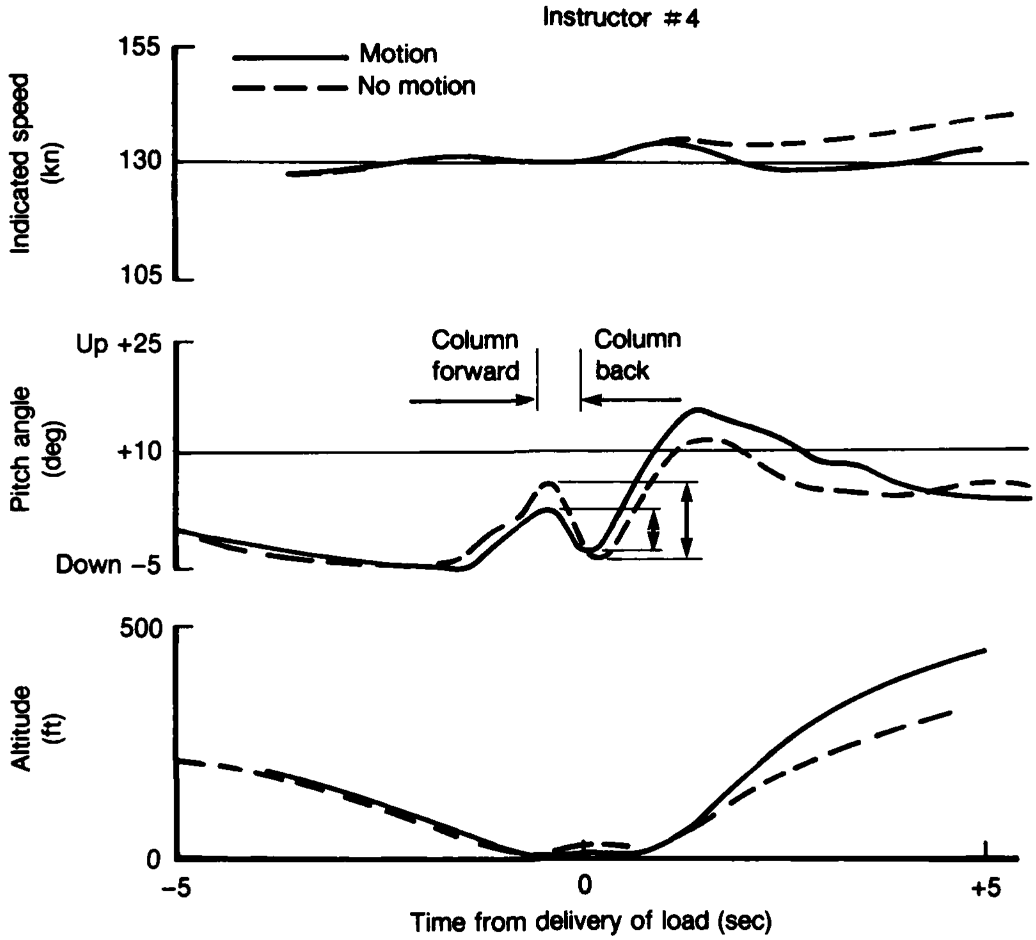


Fig. A.3 -- Effect of simulator motion on pilot (LAPES delivery)

Granting that these results may not be representative, they are in agreement with the results of previously discussed experiments and with pilot opinions expressed to the Rand team. Consequently, we are convinced that *motion does affect the way in which pilots (either experienced or inexperienced) fly the airplane.*

There remains the question of whether this difference in performance is significant so far as flight safety is concerned and whether this difference will transfer from the simulator to the actual aircraft.

Effect of Motion on the Safety of Maneuvers

To get a feel for the effect of motion on flight safety, we developed the concept of the "disaster index," which is most easily illustrated by considering the LAPES maneuver. In LAPES, the goal is to deliver the load at an altitude of ten feet and a speed of 135 kn. With the gross weight used in this experiment, the stall speed of the airplane is 104 kn. There are two possible disasters that may occur: the pilot may stall the airplane, or he may hit the ground. We may measure how far he deviated from his goal in the direction of stalling as:

$$D_s = (135 - V_{min})/(135 - V_{stall})$$

where D_s = disaster index for stall,

V_{min} = lowest indicated speed reached during the maneuver (kn),

V_{stall} = stall speed at the LAPES gross weight and configuration (104 kn in this case), and

135 = desired speed (kn).

Similar criteria can be developed to measure the danger of hitting the ground as:

$$D_g = (10 - h_{min})/10$$

Where D_g = disaster index for hitting the ground,

h_{min} = minimum altitude reached in the maneuver (ft), and

10 = desired delivery altitude (ft).

By calculating the disaster index for each mode and selecting the greatest of them,[4] a single measure of the safety of the maneuver is obtained. By comparing disaster indexes with and without motion, an indication of the effect of motion on safety can be obtained, even if different pilots approach different types of disaster.

---

[4]The larger the disaster index, the closer the pilot approached disaster.

Other maneuvers may have more than two disaster modes. For example, engine failure in takeoff involves possible wing stall, fin stall, or contact with the ground; engine failure during an ILS approach involves possible wing stall, contacting the runway at too high a vertical velocity, missing the runway laterally, or missing the touchdown aim point longitudinally.

Figure A.4 shows the results when we apply this approach to engine failure on takeoff, engine failure during ILS approach, and LAPES delivery.[5] Figure A.4 shows that the greatest differences in disaster index due to motion occur on the ILS approach task, and that copilots had higher disaster indexes than the instructors on both the ILS approach and the engine failure on takeoff tasks. Again, we caution

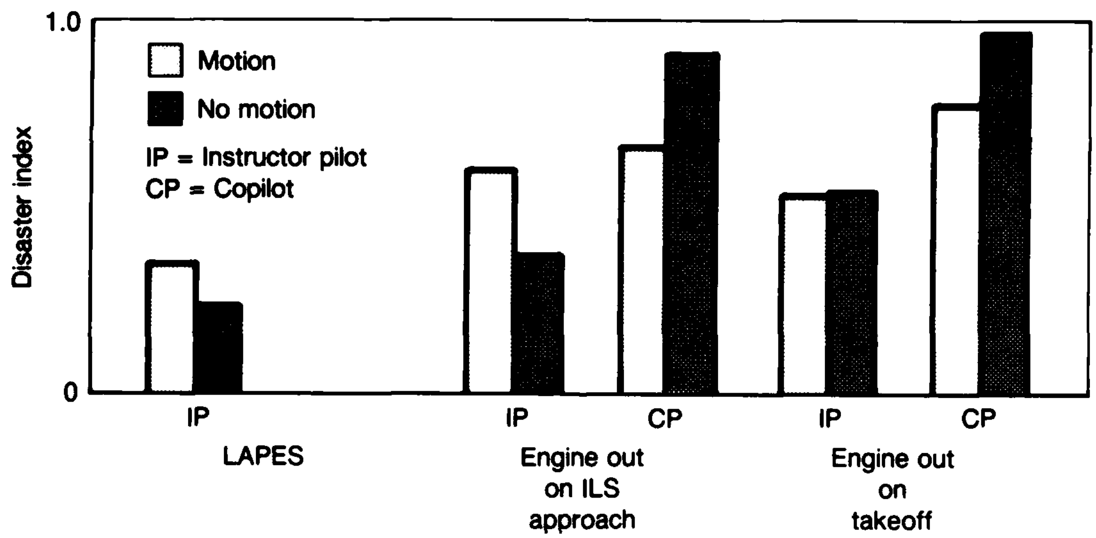


Fig. A.4 -- Effect of motion on disaster index

[5]For ILS approach, the goals were determined using a stall speed of 100 kn, a maximum vertical velocity at touchdown of 16 ft per sec, and a 150-ft-wide runway. For engine failure on takeoff, the goals were determined using a stall speed of 110 kn and a desired altitude of 1,000 ft.

that these are only sample results; they have no statistical significance.[6]

The proper way to interpret such results (assuming they were statistically significant) should not focus on whether the disaster index is higher without motion than with, but rather on whether motion causes a significant difference in the disaster index. If, for example, a statistically significant experiment shows a disaster index on a particular task of 0.2 with motion and 0.8 without, it might be concluded that, unless very favorable evidence of transfer of training is obtained, this task should not be trained without motion. On the other hand, if the disaster index is 0.2 with motion and 0.22 without, and transfer of training is well established, then this task might well be trained without motion.

---

[6]Each bar in Fig. A.4 represents the results of two trials.

Appendix B

AIRCRAFT FEATURES INFLUENCING MOTION OF THE C-17

by
W. L. Stanley

The C-17 has been designed to deliver cargo from main operating bases in the United States to main operating bases in the European theater and elsewhere, much as the C-5 and C-141 operate today. However, the C-17 will also deliver cargo directly to small austere airfields (SAAF), a mission that today requires the strategic airlift capabilities of the C-5 and C-141 and the intratheater airlift capabilities of the C-130. For this direct delivery mission, the C-17 will incorporate design features that allow short takeoff and landing (STOL) operations.

The motion cues[1] the pilot will experience in the C-17 and that he should consequently experience in the C-17 flight simulator are influenced by the aircraft's

- Size
- Design features
- Flight maneuvers.[2]

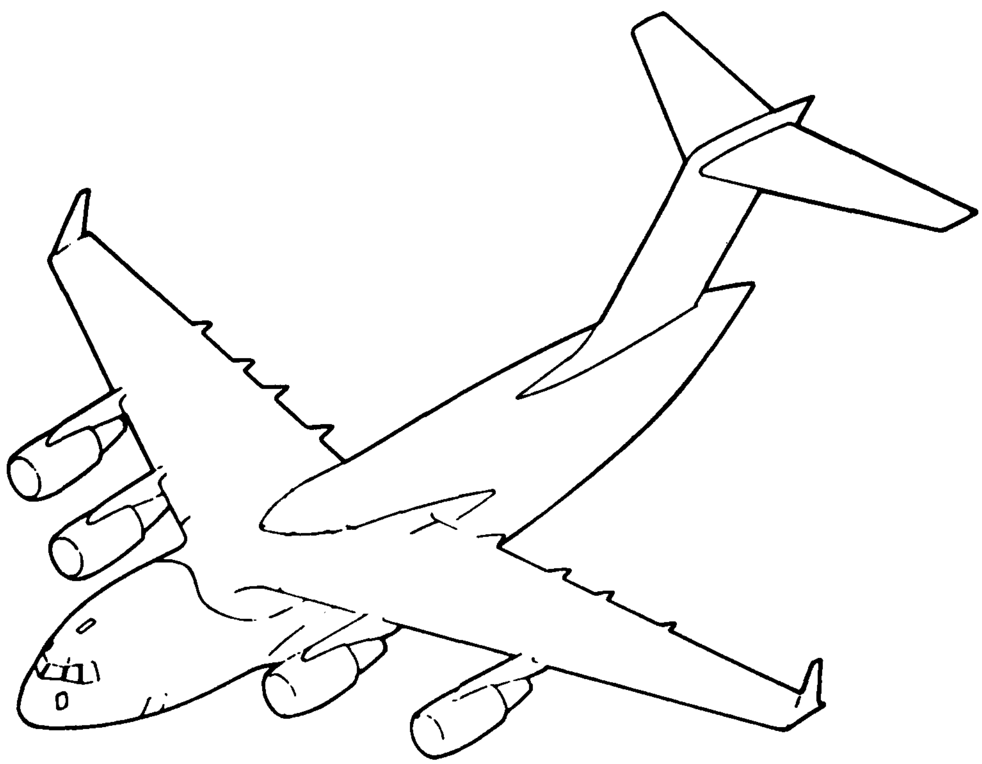
---

[1]Vehicle accelerations lead to force cues which are followed by motion of the vehicle. Nonetheless, in the lexicon of the simulator world, one usually refers to *motion cues* rather than *force cues*. In the flight test community, *force cues* are often associated with control system forces, but the simulator community sometimes substitutes the term *force cues* for *motion cues*. Unless otherwise noted, our use of the terms *acceleration cues*, *force cues*, or *motion cues* in subsequent sections is meant to be consistent with the simulator community's traditional meaning. Appendix E describes the specific motion cues associated with particular flight maneuvers and used in our simulator training capability assessment.

[2]The following descriptions rely on discussions with Douglas Aircraft Company engineers and pilots and on material contained in the following documents: *Prime Item Development Specification for C-17 Air Vehicle*, 1983; Wood et al., 1977.

SIZE

The C-17 is a large aircraft (see Fig. B.1) capable of carrying outsized cargo. However, it will have to perform flight maneuvers that are even more stringent than those of the C-130. When the C-17 rotates in pitch or yaw, the pilot--displaced 60 ft from the aircraft center of gravity (cg)--will primarily experience vertical or lateral accelerations. (By contrast, a fighter pilot sits much closer to his aircraft's cg and experiences a more pronounced sensation of angular acceleration.) On rotation at takeoff, the C-17 pilot will experience a vertical displacement of about 14 ft, more than double that typically



SOURCE: Douglas Aircraft Company, *C-17 Preliminary Design Review (PDR): Reliability and Maintainability*, May 1985, p. 531.

Fig. B.1 -- A view of the C-17

experienced by a fighter pilot. In a crosswind landing approach, the C-17 pilot might experience a yaw rotation of 10 degrees, which would displace him laterally more than 10 ft. The C-17's outboard engines are 47 ft from the aircraft centerline, compared with about two ft for a twin-engine F-15. This means that in an engine-out situation the C-17 would experience a yawing moment much greater than that for a fighter.

DESIGN FEATURES

Five prominent design features distinguish the C-17 from other Air Force transports:

- Propulsive lift
- In-flight thrust reversing
- Direct lift control spoilers
- Stability and control augmentation system (SCAS)
- Two-man cockpit

These new design features will in turn also introduce the possibility of new failure states.

Propulsive Lift

Using technology proven in the smaller YC-15, engine thrust will be directed against and over large trailing edge double-slotted flaps to generate propulsive lift that will permit greatly reduced speeds for approach and landing on small austere airfields. At full flap settings on STOL approaches, 40 to 50 percent of lift will be thrust-related, including that produced by turning the engine thrust along the lower surface of the flap and by turning it along the upper surface through the slots. Engine failures will have new implications with such an arrangement, for lift as well as thrust will be lost when an engine fails.

In-Flight Thrust Reversing

While commercial transport aircraft routinely use thrust reversers and fighters (like the Viggen and MRCA) occasionally use them *on the ground*, the C-17 will have the capability of employing its thrust reversers *in flight* to make rapid descents.

Direct Lift Control Spoilers

The C-17 will use direct lift control (DLC) spoilers that can kill lift and control position along the glideslope without appreciable changes in pitch angle or airspeed. The pilot will modulate them by using a button or switch mounted on the throttle.

Stability and Control Augmentation System

The C-17 will have a three-axis stability and control augmentation system (SCAS) working full time to improve handling qualities and reduce the pilot workload, particularly at low dynamic pressures characteristic of STOL operations. Because it will tend to attenuate motion cues felt by the pilot, the SCAS will play a major role in determining the overall motion environment in the cockpit. For this reason, Appendix C examines how the SCAS may influence C-17 motion cues.

Two-Man Cockpit

The C-17 crew will include a pilot, copilot, and loadmaster. This may mean a higher task loading for the two crewmen in the cockpit, which could be made either more difficult or more easy by the presence of motion cues, depending on the situation.

Failure States

The new design features of the C-17, while adding to its capabilities, will also introduce the possibility of new failure states, many of which could have pronounced motion cues. Table B.1 indicates the design failure states.

Table B.1

DESIGN FAILURE STATES FOR THE C-17

System	Number of Design Failure States
SCAS	6
Engine and hydraulic system	1
High lift system	2
Thrust reverser system	1
Spoiler system	6
Aileron system	4
Elevator system	5
Hydraulic system	2
Engine	2
Trim system	7
Rudder system	5

SOURCE: *Prime Item Development Specification for C-17 Air Vehicle*, 1983.

FLIGHT MANEUVERS

Many flight maneuvers of the C-17 will be very similar to those accomplished by the C-5, C-141, or C-130, and we will not dwell on those here. We will note, however, some of the more apparent differences in the C-17 training task brought about by its unique features. In some cases, the basic training task will be the same as that for other Air Force transports, but the aircraft may be controlled differently or respond differently. In other cases, entirely new devices such as the in-flight thrust reversers will be used that do not exist on other Air Force transports.

Ground Operations

The C-17 is a large aircraft, but it is designed to have a very tight turning radius so it can be maneuvered around small austere airfields. This will probably require more piloting skill for ground operations than C-141 or C-5 pilots must demonstrate. Part of the

maneuvering will involve backing the aircraft using its thrust reversers. The C-17 is being designed to back up 2 percent slopes. The C-130 can back up by reversing the pitch of its propellers, but one would expect maneuvering the much larger C-17 to be more difficult. Visual cues are more important than motion cues for such ground operations.

STOL Takeoffs

The airplane will take off at lower speeds, and hence winds will have a proportionately greater effect, although the SCAS should help the pilot. In YC-15 testing, the pilot workload was quite high for STOL crosswind takeoffs, particularly with engine failures. In the prototype program, high pitch angles required at takeoff on three engines also caused some difficulty. Because pilots were concerned about tail strikes, they tended to slow down the rotation rate and increase the ground roll, which could be critical when operating a C-17 from a 4000 ft landing strip. This characteristic may or may not carry over to the C-17, but if it does, cockpit motion cues indicating pitch rate and angle could be very important, especially since visual references are not as apparent when the cockpit rotates up.

Cruise

The Dutch roll characteristics of the YC-15 made it more challenging to control with the yaw SCAS off as altitude and airspeed increased. Whether this will occur with the C-17 is unknown, but the KC-10 also has this characteristic. To avoid damaging the airframe, there are prescribed procedures for reducing airspeed and altitude if a KC-10 pilot experiences a Dutch roll. Douglas stability and control engineers expect the airplane will be easy to fly with the SCAS off for normal missions, but only flight tests can confirm this. If the Air Force requires that C-17 pilots be able to fly the aircraft with the yaw damper off, then motion cues in the simulator may be important for learning this task. KC-10 pilots do some training in the simulator with its counterpart to the SCAS either partially degraded or, less frequently, completely turned off.

Descents

C-17 pilots will be able to make rapid descents using in-flight thrust reversing. Employment of the reversers will provide a pronounced feedback motion cue of deceleration and perhaps a continuing monitoring motion cue characterized by a certain amount of buffet. If a failure resulted in asymmetric thrust reversal, a disturbance motion cue would occur as the aircraft yawed. While the YC-15 exhibited good handling qualities even with asymmetric reverse thrust and SCAS off, this involves a new motion cue that pilots will have to master.

Glidepath Control on STOL Approaches

STOL glidepaths of five degrees (rather than the more conventional three degrees) will be flown by the C-17 using a control strategy that is the reverse of what is normally used. On the backside of the power curve, a thrust increase is required as speed decreases (this is the opposite of front-side approaches). Airspeed is best controlled by longitudinal control inputs (pitch attitude) and glidepath by power--the opposite of the front-side technique. The pilot will also be able to use DLC spoilers to rachet down to the glideslope without appreciably influencing his pitch attitude or airspeed. This should tend to simplify the control task. Although it will be important for pilots to become familiar with how the airplane responds using the backside control technique, flying the backside of the power curve and using DLC spoilers does not seem primarily to involve motion cues. The visual scene and especially instruments are more important for controlling the airspeed and the angle and rate of descent.

The slower speeds of the approach will exaggerate wind effects. In the YC-15 program, wind was the principal factor increasing the workload of STOL approaches over conventional approaches. Winds appreciably complicated the task of making pinpoint landings on short runways. Reaction time was important in adjusting power levels to hit the landing aim point. While landing is primarily a visual task, motion cues would probably provide the first indication to the pilot that he was either "floating" or "sinking," prompting him to refer to his instruments and to make power adjustments.

C-17 pilots will also have to learn to use a heads-up display (HUD) instrument for night missions, small austere airfield landings, and low-altitude parachute extraction system (LAPES) missions. Although the fighter community uses such instruments, Air Force transport pilots currently do not.

STOL Go-Arounds

The YC-15 program identified as a very demanding maneuver the transition from powered lift flight, in which a large fraction of the lift is derived from the propulsion system, to a climb condition, where the majority of the thrust vector is being utilized for forward motion and acceleration in conventional flight. In an engine-out situation, the STOL go-around was identified as the most critical and demanding maneuver in the YC-15 flight envelope. The recovery sequence involved applying maximum power, retracting the high lift flaps, rotating the aircraft after sensing the onset of longitudinal acceleration, and retracting the landing gear after a positive rate of climb had been established. *In a conventional approach, pitch attitude is increased in* conjunction with application of maximum power, flaps are retracted after the descent is stopped, and then the landing gear is retracted when a positive rate of climb is established. For a STOL aircraft, the speed change cue is elevated in importance--probably to the level of a primary feedback cue. The C-17 is expected, however, to be able to execute the go-around maneuver with better safety margins than the original configuration of the YC-15 because of its better thrust-to-weight ratio, faster flap retraction rates, the addition of an engine failure alerting system, and an improved cockpit layout.

STOL Landings

STOL landings could involve higher sink rates, and pilots will hold a constant pitch attitude to landing. The aircraft is expected to self-flare like the YC-15. Precision touchdowns and rapid braking and thrust reversing will be particularly important for landings on 4000 ft runways. Training the pilot to fly the aircraft into the ground at higher than usual sink rates would probably be enhanced in the simulator

if the pilot receives feedback motion information indicating how well he has performed. Most of the factors that influence glidepath control also pertain to the landing task--e.g., backside control, DLC, wind effects.

LAPES Missions

Using DLC spoilers to rachet down to the proper altitude for LAPES missions, and engaging the pitch-hold feature of the SCAS, make the LAPES mission different from but probably easier than performing the mission in the C-130. With the pilot fulfilling more of a monitoring role than an active role in pitch control, pitch cues brought about by the cg shift during extraction of the load should be less important. Feedback cues in the vertical axis could be important when using the DLC spoilers to set up for the LAPES run. The first indication of a DLC spoiler jam would also probably come through a motion cue.

Formation Flight

Retaining aircraft control in close proximity with another C-17 on final approach could be more challenging because of the large downwash from the high lift flaps.

Aerial Refueling

All C-5s and C-141s and some C-130s can be aerially refueled. All C-17s will be, so presumably all C-17 pilots will have to acquire this skill. Motion cues are useful in aerial refueling to help sort out who is moving, which cannot be determined merely by using visual cues.

Flying Turbofan Aircraft

C-130 pilots transitioning to the C-17 will have to learn to adjust to the different operating characteristics of turbofan engines. Power changes can be made more quickly by adjusting propeller pitch than by spooling a turbofan up or down, particularly with a high bypass ratio turbofan. This aspect of C-17 operations should obviously present no familiarization problems to C-5 and C-141 crews.

Appendix C

INFLUENCE OF THE SCAS ON C-17 MOTION

by

W. L. Stanley

The C-17's stability and control augmentation system (SCAS) will have multiple control modes in the pitch and roll axes and a damping mode in the yaw axis. Pilots will have to learn to use this system to aid in performing various maneuvers. If the KC-10 training approach is any indication, crews will also have to do some training in the simulator with various channels of the SCAS turned off. In so doing, they will learn how flying characteristics degrade with various SCAS and/or hydraulic system failures. Effectively training for these eventualities would seemingly require motion cues.

In improving handling qualities and reducing pilot workloads in both normal and abnormal situations, the C-17's SCAS is expected to attenuate motion cues that the pilot experiences. This could diminish the importance of motion information relative to other information the pilot uses to fly the aircraft. An experiment accomplished by the Air Force Flight Dynamics Laboratory in 1975 simulating a propulsive lift transport having a SCAS provides some support for this hypothesis. Investigators found that changing the aircraft's dynamic response by turning off the SCAS affected the pilot's landing performance more than turning off the simulator motion system. For some parameters, motion system effects on performance were dramatically reduced with the SCAS turned on (Gressang, 1976).

The questions about the SCAS seem particularly relevant with respect to simulator motion requirements and training in general. Will motion cues be above subliminal levels with the SCAS operating and will the piloting task become appreciably more difficult with the SCAS degraded or inoperative?

The effect the SCAS has on motion cues is also relevant to the Rand capability assessment of various simulator alternatives (see Appendix E). This assessment extended an analytical approach used by the Seville Training Systems Corporation for the FAA to determine skill and simulator requirements for airline transport pilot certification (Gilliom et al., 1984). Experienced pilots identified motion cueing information they use when performing various maneuvers with the Boeing 727-200, an aircraft whose control system has only a fraction of the capabilities of the C-17 SCAS. Hence, it was relevant to ask whether the kinds of motion cues identified in that study and used in the Rand analysis would still be usable by pilots flying a C-17 with a three-axis SCAS.

Flight test results for the YC-15, Douglas' entry in the Advanced Medium STOL Transport (AMST) prototype program, provide a means to derive estimates of the angular and linear accelerations that a C-17 pilot would experience in performing routine maneuvers, in coping with malfunctions, and in performing mission tasks (see Wood et al., 1977). These accelerations are compared with acceleration thresholds of pilots to estimate the kind of motion environment the C-17 pilot will experience.

SCAS DESIGN AND OPERATION

The SCAS augments the basic flight control system to provide "hands off" attitude-hold stability and improved aircraft response to pilot inputs. It maintains the reference attitude, altitude, or heading as selected by the pilot. Pilot force on the control wheel or column results in either a commanded attitude or attitude rate proportional to the force applied, depending on the SCAS mode selected. The pitch Command and roll Control Wheel Steering modes generate rates proportional to the control force applied and maintain the attitude existing when pressure is released. The Attitude Command mode in the pitch axis of the SCAS establishes an attitude proportional to the force applied. When pressure is released, the pitch attitude returns to a preselected reference. The yaw axis of the SCAS provides full time yaw rate damping, useful for eliminating Dutch roll (a combined lateral-directional oscillation) and for helping the pilot make coordinated turns.

Given these functional capabilities, and within its control authority limits, the SCAS can make appropriate control inputs automatically to hold the airplane attitude state even in the presence of disturbances, such as wind gusts, engine failures, cg shifts, etc., that would otherwise disturb the aircraft state and require correction by the pilot. In this way, the SCAS relieves the pilot of some of the burden of making constant corrections and reduces the amount of disturbance-induced motion he experiences.

The C-17 SCAS will have two computers per axis (pitch, roll, and yaw) and two channels per computer, or four channels per axis. SCAS commands will be summed at control surface actuators to generate the desired control surface deflection. The SCAS will command deflections up to 50 percent of maximum, so depending on the severity of a disturbance, additional pilot inputs may be required to maintain a given attitude state. With the four channels, loss of any one channel will reduce the authority of the command by 25 percent, but according to Douglas stability and control engineers, the aircraft is designed to retain good handling qualities with just one channel operating, and for less demanding applications such as logistics missions, the aircraft is expected to fly satisfactorily with no channels operating. The Mission Essential Subsystems List requires that two channels be operating at takeoff.

Given the multiple SCAS computers and channels, and extensive hydraulic system redundancy, a complete SCAS failure is extremely unlikely. Moreover, the probability of some major event such as an engine failure or asymmetrical control situation occurring simultaneously with a complete SCAS failure, making the airplane hard to handle, is even more unlikely. Multiple hits in combat would probably be the most likely scenario for such an occurrence. Given this, there will be only rare occasions when the SCAS is not operating.

While not having the level of redundancy of the C-17's SCAS, the YC-15's SCAS provided the same control authority (50 percent of the maximum deflection) and the same basic functions as the C-17's SCAS, so the YC-15 test results should provide a reasonably good indication of

how the C-17 SCAS will attenuate cues, subject to possible modest differences in the flight control hydraulic system layout between the YC-15 and the C-17 that could alter aircraft behavior somewhat in certain engine-out situations.

Used in the Seville cueing analysis (Gilliom et al., 1984) and partially in Rand's simulator capability assessment, the B-727 does not have a multi-axis SCAS analogous to that on the YC-15 and C-17. It does have a yaw damper whose design characteristics are not readily available. Even with a yaw damper, experienced B-727 pilots in that study identified primary yaw and lateral axis acceleration cues for many flight tasks. It is known that another conventional transport, the KC-10, has a yaw damper with control authority 25 percent of maximum rudder deflection, or five deg of 20 deg, in contrast to 50 percent, or 10 deg of 20 deg, for the YC-15 and C-17.

The C-17 SCAS will therefore attenuate motion cues more than the B-727 system, certainly in the roll and pitch axes for which the B-727 has no SCAS, and likely in the yaw axis, if the B-727 yaw damper has performance at all similar to that of the KC-10. The YC-15 flight test results will give an indication of how much its SCAS, having functional capabilities similar to the C-17 SCAS, attenuates motion cues.

ACCELERATION THRESHOLDS

A pilot's perception of motion cues depends on the magnitude of the applied acceleration, its duration, the axis of application, and the pilot workload. The semicircular canals of the human vestibular system act as *angular* accelerometers, although in the frequency range of most concern for flight simulation they respond like rate sensors. The otolith organs of the utricule and saccule play the role of *linear* accelerometers (Gundry, 1976).

Experiments accomplished at the MIT Man-Vehicle Control Lab have yielded the following estimates of minimum detectable *angular* accelerations (Stapleford et al., 1969):

- 0.5 deg/sec/sec for roll and pitch
- 0.14 deg/sec/sec for yaw.

Research on modeling semicircular canal dynamics has estimated time constants of pilots for each rotational axis. These can be combined with the accelerations noted above to derive the rate thresholds noted below (Stapleford et al., 1969):

- 3.2 deg/sec for roll
- 2.6 deg/sec for pitch
- 1.1 deg/sec for yaw.

We will compare the product of YC-15 angular accelerations and their duration with the threshold values shown above.

With respect to *linear* accelerations, otoliths are said to be unreliable for sensing changes below 0.005 g, regardless of duration (Young, 1980a, 1980b). Practical thresholds for fore-aft and lateral accelerations are thought to range from 0.01 to 0.02 g (van Gool, 1978b; Young, 1980b), and some references suggest the 0.02 threshold for a latency of two seconds (Cohen, 1971). L. R. Young (1980b) also says the threshold of 0.02 can probably be doubled in the presence of superimposed vibration. We will use 0.02 g for two seconds as a threshold in evaluating YC-15/C-17 linear accelerations, but we also note how higher thresholds might change conclusions.

ACCELERATIONS

To estimate the magnitude and duration of disturbance acceleration cues, we reviewed a variety of YC-15 flight test maneuvers that encompass normal maneuvers, simulated malfunctions, and mission tasks. Tables C.1 and C.2 show the accelerations and acceleration-time products for the YC-15. The linear accelerations shown for the C-17 were derived by scaling up YC-15 accelerations to reflect the fact that the distance from the cg to the cockpit is 54 percent greater for the C-17 than the YC-15 (60 ft vs 39 ft). Discussion focuses on the acceleration-time metric because it encompasses more of the parameters that influence whether a pilot perceives motion.

Table C.1

ACCELERATION CUES

	Angular Acceleration (deg/sec^2)			Corresponding Linear Acceleration (g)			
				Lateral		Vertical	
Maneuver	Yaw	Roll	Pitch	YC-15	C-17	YC-15	C-17
Left inboard engine retardation at V1							
At engine retard	1.9	1.8		.04	.06		
When roll/yaw SCAS goes to half gain	2.0	3.9		.04	.07		
Right outboard engine retardation at liftoff	2.0	3.3		.04	.07		
Left outboard engine retardation go-around	0.7	1.9		$\boxed{.01}$	.02		
LAPES delivery							
When load begins to move			7.6			.16	.25
When load exits ramp			4.9			.10	.16
Just prior to release	2.2			.05	.07		
Normal rotation and climb	1.6			.04	.05		
Normal turn							
0 deg flaps	2.9			.06	.09		
24 deg flaps	1.4			.03	.05		
46 deg flaps	2.2			.05	.07		
0 deg flaps--yaw SCAS off	2.0			.04	.06		
3-engine crosswind approach	2.0	7.8		.04	.07		
Roll SCAS failure at liftoff		3.6					
Pitch SCAS failure at liftoff			1.5			.03	.05
Roll/yaw SCAS off during cruise	3.1			.07	.10		

SOURCE: Wood et al., 1977.

$\boxed{}$ = subliminal.

Table C.2

CUE ACCELERATION-TIME PRODUCTS

	Angular Acceleration-Time Product (deg/sec)			Linear Acceleration-Time Product (g-sec)			
				Lateral		Vertical	
Maneuver	Yaw	Roll	Pitch	YC-15	C-17	YC-15	C-17
Left inboard engine retardation at V1							
At engine retard	2.3	$\boxed{1.4}$		.05	.07		
When roll/yaw SCAS goes to half gain	1.6	4.7		$\boxed{.03}$	.05		
Right outboard engine retardation at liftoff	1.3	4.5		$\boxed{.03}$	.04		
Left outboard engine retardation go-around	1.1	$\boxed{2.4}$		$\boxed{.02}$	.04		
LAPES delivery							
When load begins to move			$\boxed{2.0}$			.04	.07
When load exits ramp			$\boxed{1.0}$			$\boxed{.02}$	$\boxed{.03}$
Just prior to release	$\boxed{1.0}$			$\boxed{.02}$	$\boxed{.03}$		
Normal rotation and climb	1.8			.04	.06		
Normal turn							
0 deg flaps	2.0			.04	.07		
24 deg flaps	12.5			.27	.41		
46 deg flaps	3.2			.07	.10		
0 deg flaps--yaw SCAS off	2.7			.06	.09		
3-engine crosswind approach	2.6	8.3		.05	.08		
Roll SCAS failure at liftoff		3.3					
Pitch SCAS failure at liftoff			$\boxed{2.1}$			.04	.07
Roll/yaw SCAS off during cruise	3.8			.08	.12		

SOURCE: Wood et al., 1977.

$\boxed{}$ = subliminal.

Left Inboard Engine Retardation at V1

The left inboard engine of the YC-15 was retarded at V1 (the speed at which the aircraft is rotated for takeoff), with an associated hydraulic system failure about eight seconds later that reduced the gain of the SCAS by one-half. Table C.2 indicates yaw and lateral cues were above threshold in both cases shown for this maneuver, whereas the roll axis cue is below threshold before the SCAS goes to half gain.

Motion cues would likely be more pronounced with an actual engine flameout than with an engine pullback as was done in YC-15 flight testing, but even the flight test results suggest the cues are of sufficient size that they would alert the pilot that something had happened requiring a control response, namely aileron and rudder inputs. However, the disturbance acceleration that occurred at the time of the engine retardation and the later SCAS degradation was difficult to distinguish from the on-going accelerations the pilot was experiencing as the airplane rolled down the runway and rotated. This suggests the C-17 pilot may have difficulty uniquely associating an attenuated motion cue with an engine failure immediately, although the initial motion cue would be sufficient to trigger checks for other cues to refine his control response to the disturbance.

Right Outboard Engine Retardation at Liftoff

In this maneuver, the SCAS operated with full effectiveness. The yaw acceleration-time product was marginally above threshold, whereas the YC-15 lateral acceleration-time product was below threshold for the YC-15 and on threshold for the C-17. The roll cue was about 40 percent above threshold.

Left Outboard Engine Retardation-Go-Around

Engine number one was retarded at 500 ft above ground level and the pilot executed a go-around. The low values for the acceleration-time products indicate the difficulty of relying on motion cues to identify an engine failure on approach. This was confirmed in YC-15 test reports and in conversations with a Douglas test pilot. The SCAS should mask the rolling moment of an inboard engine failure more than an outboard

failure (Wood et al., 1977). Roughly two seconds were required to recognize an outboard failure, but six to eight seconds to recognize an inboard engine failure. Warning lights were ultimately installed in the cockpit to alert the pilot of engine failures.

LAPES Delivery

All low-altitude parachute extraction system (LAPES) deliveries in the YC-15 program were accomplished with the SCAS operating. Table C.1 indicates that pitch accelerations were quite large, particularly when the load began moving, but also when the load exited the ramp. Induced vertical accelerations were well above threshold. The yaw acceleration before the delivery with the drogue out, the rear doors open, and the ramp down were also above threshold.

Examination of Table C.2 indicates that the duration of the pitch accelerations when the load exited the ramp was sufficiently small that the acceleration-time product was below threshold, as were the yaw and lateral acceleration-time products prior to release. These results illustrate how the SCAS can quickly correct for disturbance accelerations caused by movement of the cg.

Normal Rotation and Climb

The Seville study cites yaw as an onset cueing source for many phases of flight, including rotation and climb. All values are above threshold for this maneuver.

Normal Turns

Yaw accelerations are said to be an important cue for turns as well, and all values are above threshold, even with the yaw axis of the SCAS helping to keep turns coordinated. With the yaw axis of the SCAS turned off, but with the roll axis operating, accelerations and acceleration-time products were above threshold, as the aircraft experienced a Dutch roll during the turn.

Three-Engine Crosswind Approach

With one engine at idle, accelerations and acceleration-time products for a crosswind approach were above thresholds.

Simulated Roll SCAS Failure at Liftoff

With a simulated roll SCAS failure two seconds after liftoff, the roll acceleration-time product is slightly above threshold.

Simulated Pitch SCAS Failure at Liftoff

The pitch acceleration-time product was not above threshold in this case, although the vertical axis acceleration was.

Roll/Yaw SCAS Off during Cruise

With the roll and yaw SCAS turned off, a rudder input by the pilot induces an undamped Dutch roll oscillation. All accelerations were well above threshold, as were acceleration-time products.

SUMMARY OBSERVATIONS

If the favorable handling qualities demonstrated by the YC-15 carry over to the C-17--and that can only be conclusively demonstrated with flight testing--then C-17 disturbance acceleration cues will not be large. For most maneuvers, they should be sufficient to serve as an alerting function for the pilot, even with the SCAS operating.

Only during certain aspects of LAPES deliveries and in a Dutch roll with the roll and yaw SCAS turned off were lateral and vertical acceleration cues equal to or greater than 0.1 g. The most pronounced accelerations in the yaw axis occurred in a Dutch roll with the roll and yaw SCAS turned off. The most pronounced pitch axis accelerations occurred during a LAPES delivery and the largest roll acceleration occurred during a three-engine crosswind landing. For acceleration-time products, the largest yaw axis value occurred during a normal turn, the largest roll axis value for the three-engine crosswind approach, and the largest pitch value during a pitch SCAS failure at liftoff.

For each maneuver examined, acceleration-time products in at least one C-17 axis fell above threshold levels.

Given the magnitude of normal "background" accelerations, C-17 pilots may have difficulty uniquely associating a disturbance acceleration with a particular event, but the cue will alert the pilot to take certain control actions or to evaluate other sources of cues. A simulator with motion could potentially have value in teaching pilots to respond correctly to more subtle motion cues.

Even normal flight maneuvers such as cruise and coordinated turns can become more challenging without SCAS, and they can involve some of the larger accelerations examined in this analysis. Hence, there may be value in using a simulator with motion to learn to fly the aircraft with a degraded or failed SCAS. KC-10 pilots do a limited amount of training in the simulator with the KC-10 "SCAS" degraded or turned off.

The absolute levels of the disturbance accelerations examined in this analysis do not approach the limits of six-degree-of-freedom platforms. The cyclic rates such as those encountered in a Dutch roll with the SCAS off are also within the capabilities of modern platforms. Larger accelerations normally encountered in turning, braking, etc., will set motion requirements.

Appendix D

FIDELITY OF DIFFERENT MOTION CUEING ALTERNATIVES

by
W. L. Stanley

In identifying alternatives for providing simulator motion, we selected the best-performing example of each generic type that had some prospect of filling the C-17 training need. This facilitated comparisons across motion alternatives because if one generic alternative performed better than another, we could be confident that it was not because we had selected an inferior performing example of the competing generic device.

Numerous motion cueing devices have been proposed and/or used to satisfy various simulator motion requirements. For each generic type of motion device, we applied the following screening criteria to narrow the list of alternatives:

1. Reject alternatives (like g-suits) that are incompatible with transport operations.
2. Reject alternatives (like helmet loaders) that cannot treat mission-critical requirements.
3. Consider only production alternatives that have been used in training.
4. Choose alternatives that provide the most complete set of cues.

These criteria led us to reject such devices as g-suits, helmet and arm loaders, and a host of other motion cueing techniques designed for high-g fighter simulator applications. However, one device originally designed for fighter simulator applications, the g-seat, was retained because some have suggested it might satisfy transport simulator motion requirements.

The three alternatives evaluated in the Rand assessment were

- A simulator having a fixed base
- A simulator using a six-dof motion platform, the current standard for transport aircraft simulation
- A simulator using a hydraulic/pneumatic g-seat

This narrowing of the motion alternatives to three cases not only aimed at keeping the analysis manageable but also reflected some technical and commercial realities. As we shall subsequently see, even the most capable g-seat has difficulty supplying a full range of motion cues, and hence it would be pointless to evaluate lower-fidelity g-seats.[1] Motion platforms with fewer than six dof--but having at least three and preferably four dof (pitch, roll, vertical, and lateral)--might satisfy many military transport simulator requirements, but the industry standard today is the six-dof synergistic platform, and industry is geared to produce that type of motion device in quantity for civil and military customers. Few manufacturers even produce large-payload, three-dof platforms today.[2]

FIDELITY OF SIX-DOF MOTION PLATFORMS

Technological improvements have enhanced performance and availability of contemporary motion platforms such that they enjoy widespread use and acceptance by the transport pilot community.

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[1]As used here, *fidelity* is the extent to which a simulator motion alternative can adequately represent the motion information needed by pilots to fly transport aircraft.

[2]One major manufacturer suggested the most cost-effective way to supply less than six dof would be to use six-dof hardware and alter the software drive algorithms. Another suggested a comparatively small cost advantage from going to a new design with fewer dof. In any event, such internal capability tradeoffs for a given generic class of device can always be explored after deciding on the most attractive motion alternative.

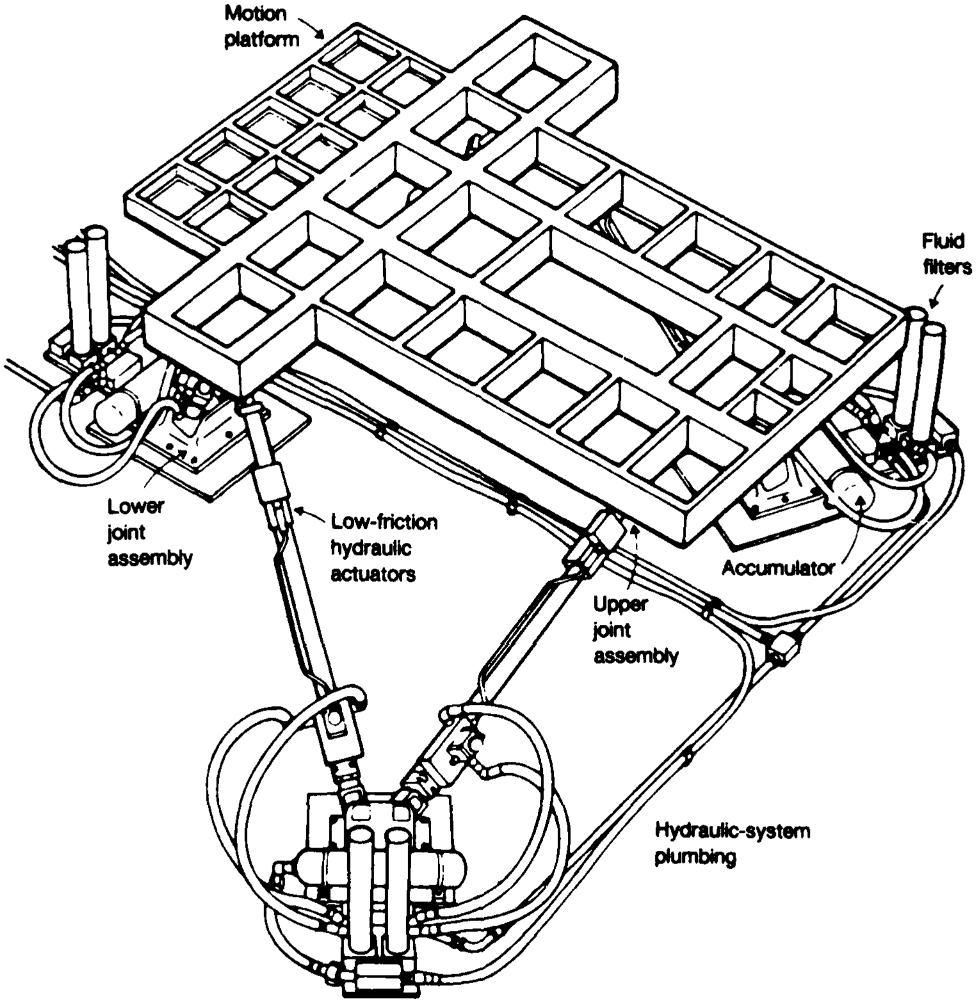
Design Characteristics

Platform Hardware. The six-dof synergistic platform design was introduced in the early 1970s to satisfy airline simulator motion requirements. As Fig. D.1 illustrates, the synergistic design has several desirable attributes, including a relatively simple mechanical structure and extensive parts commonality. Logistics support for the device is simplified because each platform uses six identical hydraulic jacks or actuators, six identical electro-hydraulic control systems, and three identical base pads and platform mountings.

Manufacturers have largely overcome several serious shortcomings of first-generation hardware. The most significant problems were an objectionable turnaround bump, sometimes referred to as "burble," that occurred as the hydraulic actuators reversed direction, and a lack of smoothness when running at high velocity, called "rumble." These characteristics detracted from the realism of the motion simulation and during certain situations--such as ILS approaches--pilots would make control inputs in response to these spurious motion cues. Unfortunately, many experiments evaluating the value of motion in aircraft simulation used platforms having these characteristics (see Appendix A).

Manufacturers determined that cylinder seal friction in conventional hydraulic cylinder designs, and large pressure changes that occurred when an unbalanced area cylinder reversed direction, caused the turnaround bump and that hydraulic noise at high velocities caused the rumble. The use of hydrostatic bearing technology and asymmetric servovalves has now virtually eliminated the turnaround bump. The hydrostatic cylinder design eliminates the use of high-pressure seals, and it floats the piston and rod on a film of fluid to keep them out of contact with the cylinder. Friction has been reduced by 80 percent over conventional cylinders. The asymmetric servovalve balances the flows of hydraulic fluid on each side of the piston to eliminate pressure changes when the cylinder reverses.

These design changes, incorporated in most platforms delivered since the mid-1970s and motivated by performance shortcomings, have had a beneficial effect on platform availability as well. There is



SOURCE: The Singer Company, Link Flight Simulation Division

Fig. D.1 -- Six-dof synergistic motion platform

virtually no wear between moving and stationary members. Only low-pressure seals are required and lower operating pressures are possible, which reduces the leakage problems that plagued first-generation devices. Most maintenance consists of inspecting and changing filters and fluids as necessary. The net result is that modern motion systems are not a significant contributor to simulator unavailability. Table D.1 summarizes some of the motion platform improvements noted above.

Software/Computing. Although motion drive software is not a large consumer of computer memory or time, computing resources were sufficiently precious in early platform implementations that compromises were sometimes struck between motion and other computing needs. These compromises detracted from the quality of the motion cueing delivered to the pilot. Low program update rates in some implementations contributed

Table D.1

MOTION PLATFORM IMPROVEMENTS

Parameter	Early/Mid-1970s Devices	Current Devices
Hydraulic pressure (psi)	2000	1200-1800
Turnaround bump		
-- breakaway force (lb)	600-1200	<100
-- acceleration (g, peak to peak)	.1-.2	.04
Rumble noise (g, peak to peak)	.04	<.015
Dynamic response (hz)	2	4
Response time (msec)	200-400	<100
Computing update rate		
-- basic program (hz)	7.5	20
-- output to hardware (hz)	30	40
Acceleration		
-- long., lat./heave axes (g)	.6/.8	.5-.8/.6-.8
-- angular (deg/sec^2)	50	60-120
Velocity		
-- linear (in/sec)	24	24-34
-- angular (deg/sec)	15	16-24
Availability (%)	?	>99

SOURCES: Simulator SPO; motion platform manufacturers; Albery et al., 1978; Baret, 1978; Gebman et al., R-3276-AF, 1986; McKinnon, 1981; Viersma and Baarspul, 1980.

to abrupt motion, large time lags between pilot control inputs and the response of the platform, and between display of visual and motion cues (Gum and Albery, 1977). When motion platform response-time-lags reach 200 msec or more, as indicated in Table D.1, there is some evidence that pilot performance begins to suffer. Today's simulators are not so constrained by computing resources, and the response time of modern platforms is well within tolerable limits.

Platforms and computing hardware have evolved so that today they usually do not detract from the flight simulator's ability to display adequate motion cues. However, two other critical elements still occasionally detract from the simulator's ability to provide good motion cueing:

- Software drive algorithms
- Supporting aircraft data

Software drive algorithms strive to match simulator and aircraft acceleration profiles within the excursion limits of the simulator motion platform. Some of the many algorithms include proportional drive, clipped drive, linear washout, coordinated linear washout, adaptive linear washout, and nonlinear adaptive washout, each having advantages and disadvantages (Young, 1980a). Both research and operational experience has shown that pilot complaints about motion fidelity are often traceable to shortcomings in motion drive algorithms.

Research accomplished at the NASA Langley Research Center has emphasized the development of advanced cueing algorithms following an overall principle of minimizing false cues even at the expense of not displaying some correct cues, because of pilot sensitivity to false motion cues. Their nonlinear adaptive washout algorithm has achieved favorable transport pilot acceptance and has even demonstrated its value in simulating the motion environment associated with some types of fighter aircraft maneuvers (Parrish, 1978). These computationally more complex but more capable algorithms are now being introduced in the commercial environment. Their introduction should better exploit the improved performance characteristics of new motion platform hardware.

The absence of adequate aircraft data has been a chronic impediment to effective aircraft simulation through the years. The problem persists today as simulators are being upgraded or replaced for aircraft that underwent flight test years ago when high-fidelity simulators were not an important element of training and consequently were not a consideration in determining the flight test data to be collected. For example, a lack of good ground-effects flight-test data for the C-130 has complicated recent efforts to improve the landing maneuver fidelity of the Air Force's C-130 simulators.

The need for higher-fidelity modeling of flight characteristics--and particularly the landing maneuver in ground effect in airline simulators beginning in the mid-1970s--has generated a greater awareness of the shortcomings of aircraft data packages. Major commercial aircraft manufacturers now routinely collect the aircraft data necessary to support FAA Phase I, II, and III simulator fidelity requirements. There are no major technical impediments to collecting the necessary data, although for reasons of safety, some "lateral" data are not collected close to the ground at low speeds. Much of the flight-test data routinely collected for the estimation of performance, stability and control, and flying qualities can also support simulator data needs, but the modeling of some flight phases in the simulator (such as landing) requires more precision in data collection. Ground effects data are typically collected by carefully flying the aircraft in a particular configuration at a constant low altitude and speed and collecting data on how the aircraft responds. This is repeated for different altitudes, speeds, and configurations to build up a set of data that can then be reduced and incorporated into the simulator data package.

In summary, having a good aircraft data package is critical to the adequate representation of motion cues. Failure to make adequate provisions in an aircraft program to collect the aircraft data to support the simulator can severely compromise not only the considerable investment in motion system hardware and software but also the training potential of the simulator.

Platform Performance

In principle, the six-dof synergistic platform can represent all the kinds of motion information that pilots typically use to fly transport aircraft, although its synergistic operation means that movement in any one dof is often at the expense of movement in the other axes. A continuing challenge for designers of cueing algorithms is to identify the most desirable motion tradeoffs among axes for particular aircraft applications. Table D.2 illustrates how the six axes of a platform supply motion cueing information typically used by transport pilots.

The strength of the motion platform is its ability to generate onset cues in each axis that can stimulate the human vestibular system. By rolling or pitching in a subliminal manner (the so-called gravity alignment technique), the platform can also generate sensations of

Table D.2

HOW SIX-DOF PLATFORMS DISPLAY MOTION CUES

	Platform Movement					
Type of Information	Longitudinal Translation	Lateral Translation	Vertical Translation	Pitch	Roll	Yaw
Constant g-loading			O	S		
Constant deck angle			O	S		
Change in pitch			O	S		
Buffet pitch			O/S			
Change in speed (accel/decel)	O			S		
Change in roll		O			O/S	
Buffet roll					O/S	
Uncoordinated flight (yaw out of trim)		O			S	
Change in yaw		O			S	
Buffet yaw		O/S				

O = onset; S = sustained
SOURCE: Adapted from Gilliom et al., 1984.

sustained cues, particularly for transport aircraft that typically experience far lower sustained accelerations than would fighter aircraft.

Table D.2 illustrates how a motion platform can use two separate axes to supply the onset and sustained component of a cue. For example, the onset of a longitudinal acceleration is supplied by a longitudinal translation of the platform, whereas the sustained cue is supplied by subliminally pitching the cockpit. This uses the gravity vector to provide a sustained sensation of being pushed into the seat, such as would occur as an aircraft accelerates.

The six-dof platform has the greatest difficulty representing roll cues, since it must do so in a one-g environment. A simple roll of the platform introduces a false side force that would not be present in an aircraft executing a coordinated turn. Translation of the platform laterally can diminish but not remove the side force, at least in training simulators not having the extensive lateral excursion capability of some research simulators (three to five ft vs 100 ft). In practice, the roll cue tends to dominate, particularly for moderate roll angles of less than five or six degrees, and hence pilots usually do not find representation of the roll cue objectionable (Parrish, 1978).

Comparison of transport and motion platform performance suggests that the magnitude of onset cues generated by motion platforms is adequate to simulate most transport maneuvers, recognizing that a one-to-one correspondence between aircraft and simulator accelerations and rates is not necessary for effective simulation. Table D.3 compares the rates and accelerations characteristic of military transports, the YC-15, and current generation motion platforms. The values for the YC-15 shown in Table D.3 represent some of the largest rates and accelerations it demonstrated during flight test, and all are essentially within the performance envelope of contemporary platforms, albeit their independent axis performance envelope. The maximum roll rate for a typical military transport falls outside the envelope, but if YC-15 flight-test results are any indication, maneuvers at such roll rates would be rare. Most significantly, with the exception of the three-g limit load factor for a lightly loaded transport, the other

Table D.3

COMPARISON OF AIRCRAFT AND PLATFORM MOTION CAPABILITIES

	Military Transport Performance		Current Six-dof Platform Performance
Motion Parameter	Maximum	YC-15 flight test	Independent axis capability
Angular rates (deg/sec)			
Pitch	20	7	20
Roll	60	17	20-23
Yaw	10	8	20-24
Angular accelerations (deg/sec^2)			
Pitch	25	13	60-100
Roll	60	26	60-100
Yaw	8	7	60-100
Linear accelerations (g)			
Longitudinal	.3	.15	.6-.7
Lateral		.14	.6-.7
Vertical	-1,+3	2.0	(1).8
Time to respond to control input (milliseconds)	75		<100

SOURCES: Airframe manufacturers; motion platform manufacturers; Wood et al., 1977.

critical accelerations that provide initial force cues fall within the performance boundaries of the platform.

This brief discussion of platform fidelity illustrates some of the reasons why transport pilots have generally expressed satisfaction with the motion cues provided by modern motion platforms that use effective drive algorithms and that incorporate good data-base representations of aircraft characteristics through the flight envelope.

FIDELITY OF G-SEATS

The g-seat is an intermediate motion cueing option between a six-dof platform and a fixed-base simulator. This subsection assesses the adequacy of its motion cues for transport aircraft simulation.

Philosophy behind G-Seats

Motion is sensed through haptic, vestibular, and visual cues, normally in that order set by the dynamic response of each sensory system. Inertial movement of a motion platform stimulates the vestibular senses and, as a by-product of that motion, the haptic system is stimulated as well. Excursion constraints of platforms limit their ability to present sustained acceleration cues, although gravity-alignment techniques help some in this regard. G-seats, on the other hand, are designed to stimulate the haptic sensory system directly, which encompasses the perception known as "body feel." The principal elements of the haptic system include the senses of touch, temperature, pressure sense, muscle sense, and skeletal joint sense. Physiological changes due to motion usually manifest themselves in terms of skeletal attitude changes, muscle tonal changes, pressure changes, and touch/area of contact changes.

When g-seats were initially developed, designers thought they might have a role in both complementing and to some degree substituting for platform motion. The g-seat was to complement the onset cueing capability of the platform by directly stimulating the haptic system to represent sustained cues by altering the linear position, attitude, and contour of seatpans and backrests to provide a facsimile of the coupling experienced between a pilot's body and his seat induced by rotational and translational accelerations of an aircraft. Designers thought that by taking some of the cueing load off the platform, the g-seat might also relax some of the platform's design requirements. This initial view of the g-seat has changed to the point that g-seats are now being designed that manufacturers claim have onset cueing capability. The military services are procuring fighter aircraft simulators that use g-seats without motion platforms.

Kinds of G-Seats

Table D.4 summarizes some of the key characteristics and performance of the three basic kinds of g-seats:

- Pneumatic bladder seats
- Pneumatically driven metallic bellows seats
- Combined pneumatic bladder/hydraulic seats.

The first two kinds of pneumatic-only seats differ in that the first uses simple pneumatic bladders mounted on top of a hard backrest and seatpan, whereas the bellows seat has metallic chambers having internal springs with rigid top plates mounted above the bellows. The bellows seat is more complex and by nature of its design requires higher operating pressures than the bladder seat (12 psi vs 2 to 3.5 psi). Both suffer from poor response time and are limited in frequency response as well. Most pneumatic bladder seats, especially the less expensive ones, generate only about 0.5 inches of linear excursion and 2 deg of angular excursion, so the bellows seat can move the pilot around much more than the average bladder seat, but with a corresponding increase in complexity and cost.

The hydraulic/pneumatic seat can move the pilot around even more through the combined action of its pneumatic and hydraulic drives. In addition, its hydraulic components give it much better frequency response and response time than the pneumatically driven seats, but this type of seat is also quite complex and expensive.

Applications of G-seats

Each kind of g-seat noted above has been manufactured and used for either research or operational training. There would be little or no hardware development risk in procuring such seats, although as we shall discuss subsequently, there is still much uncertainty about the most desirable drive algorithms for such seats.

Table D.4

G-SEAT CHARACTERISTICS AND PERFORMANCE

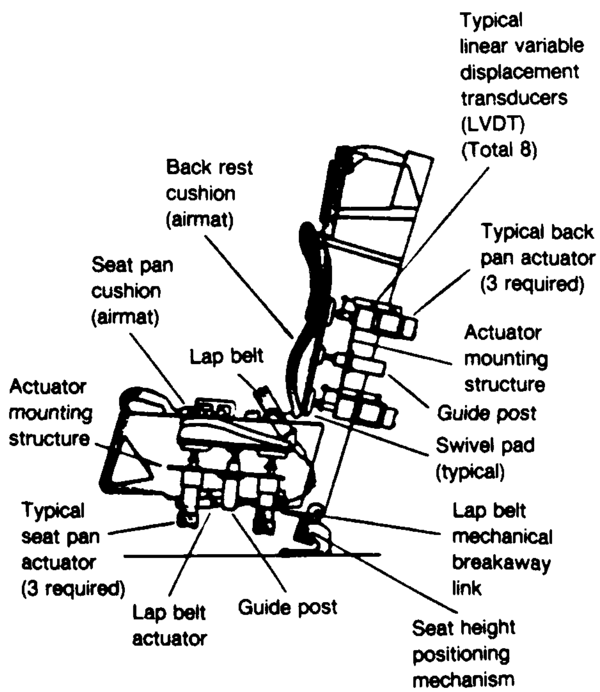
Parameter	G-seat Type: Pneumatic Bladder	Pneumatic Metallic Bellows	Combined Pneumatic Bladder/ Hydraulic
Active seat elements (no.)			
Pneumatic drives	1-9	30	3-8
Hydraulic rams	NA	NA	6-11
Lap belts	0-2	1	2
Maximum pneumatic pressure (psig)	5	12	3.5
Linear excursions (in)			
Pneumatic	+/- .5-2	+/- .9-1.4	+/- .5
Hydraulic	NA	NA	+/- .8-1.3
Angular excursions (deg)			
Pneumatic	+/- 0-8	+/- 6-10	+/- 0-2
Hydraulic	NA	NA	+/- 0-12
Bandwidth (hz)	1-6	.5-1.9	Pneu. 1-6 Hydr. 5-10
Response time to 63% amplitude (msec)	50-70	80	Pneu. 30-85 Hydr. 30-40

SOURCES: Albery and Hunter, 1978; Albery et al., 1978; Ashworth, 1976; Ashworth et al., 1977; Ashworth et al., 1984; Bose et al., 1981; Kleinwaks, 1980; Kron, 1976; McKissick et al., 1980; Ricard et al., 1981; Showalter, 1978; Showalter and Parris, 1980.

Bladder seats are primarily used in fighter/attack aircraft training simulator applications and for simulator research across a variety of fixed and rotary wing aircraft types. For example, the A-10 simulator uses a bladder seat manufactured by Reflectone, while most of the experimental results reported on bladder seats have used the NASA Langley seat design, which has four cells in the seatpan and four cells in the backrest.

The bellows seat manufactured by Link has been used in the Advanced Simulator for (Undergraduate) Pilot Training--AS(U)PT--at the Air Force Human Resources Laboratory (AFHRL) for all their g-seat experiments as well as for transport aircraft experiments at NASA Ames. The same basic seat is also installed in the Simulator for Air-to-Air Combat (SAAC) at Luke AFB, which has both a research and training role.

Hydraulic/pneumatic seats have been used in comparatively few applications. F-15 flight simulators for the USAF and Saudi Arabia use Goodyear Aerospace hydraulic/pneumatic seats. Goodyear has delivered three to the USAF. Figure D.2 depicts the arrangement of such a seat. Link has manufactured and delivered to the USAF a more complex hydraulic/pneumatic seat, the one-of-a-kind Advanced Low-Cost G-Cueing System (ALCOGS), that proved to be, despite its name, very expensive.



SOURCE: Goodyear Aerospace Corporation

Fig. D.2 -- Hydraulic/pneumatic g-seat arrangement

The Air Force Aerospace Medical Research Laboratory and the Aeronautical Systems Division are now jointly using this seat for research purposes.

This review identified no transport aircraft training simulators that use g-seats of any kind. NASA has used g-seat cueing in two experiments involving B-737 and KC-135 aircraft.

How G-Seats Present Cues

G-seats rely on the symmetric or asymmetric inflation and deflation of pneumatic bladders or bellows, the translation and rotation of seatpans and backrests by hydraulic actuators, and the constriction or relaxation of lap or shoulder harnesses by pneumatic or hydraulic actuators to impart motion cues. The left portion of Fig. D.3 illustrates the degrees of freedom available with a hydraulic/pneumatic g-seat such as that used in the F-15 simulator. The right portion of Fig. D.3 illustrates some of the motions available with a pneumatic seat having nine elements in the seatpan. The ALCOGS research seat has some

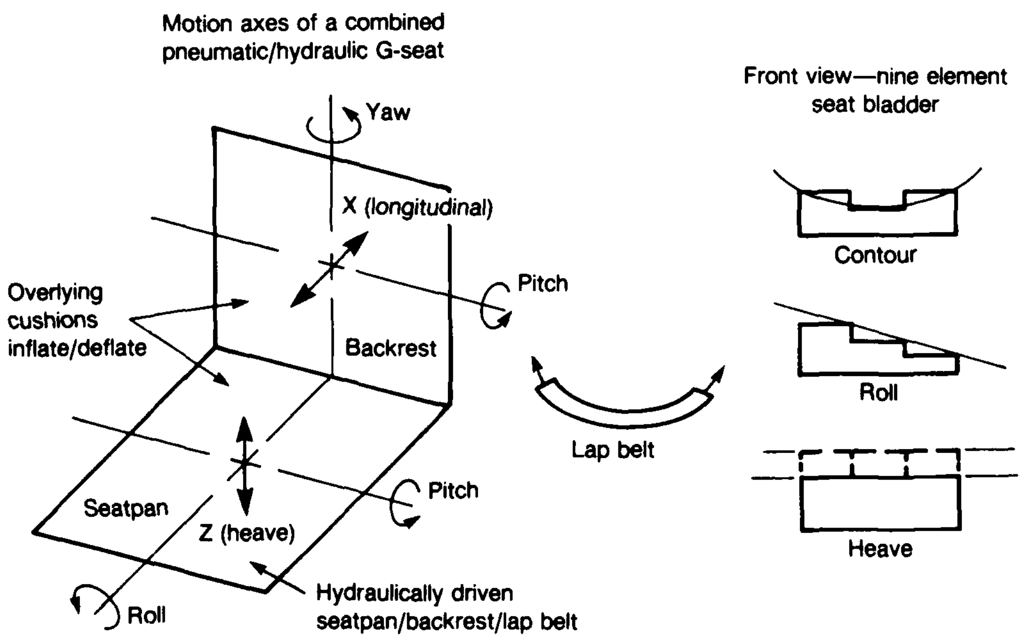


Fig. D.3 -- G-seat motion axes

additional motions not depicted in the figure, including fore-aft translation of the seat pan and some inflatable side panels to provide more direct side forces.

Tables D.5 and D.6 illustrate how the pneumatically and hydraulically driven elements of a typical g-seat use the degrees of freedom illustrated in Fig. D.3 to reproduce the required accelerations at the pilot position by axis.

The motion representations shown in Tables D.5 and D.6 were used to determine whether and how a g-seat could represent the ten kinds of motion information identified by transport pilots in the Seville analysis (Gilliom et al., 1984) and used in the Rand simulator capability assessment. Table D.7 shows those ten kinds of motion information in the left column, followed by the seat motions that provide onset and sustained manifestations of those aircraft motions. The cue construction on the right of the chart shows that some motions experienced at the pilot position are composites of two basic aircraft motions. The last two columns will be used subsequently in assessing the quality of the cues presented. The key finding displayed in Table D.7 is that, in one way or another, the design of the hydraulic/pneumatic g-seat provides some kind of representation for each

Table D.5

PNEUMATIC COMPONENT OF G-SEAT MOTION REPRESENTATION

Pilot Position Acceleration Axis	Seatpan				Backrest			
	Contour	Roll	Pitch	Heave	Contour	Pitch	Yaw	Fore-aft
X			*		*	*		*
Y		*					*	
Z	*			*		*		
Roll		*					*	
Pitch			*					
Yaw								

SOURCES: Ashworth, 1976; Ashworth et al., 1977; Ashworth et al., 1984; Kron, 1976; McKissick et al., 1980; Ricard et al., 1981; Showalter, 1978.

Table D.6

HYDRAULIC COMPONENT OF G-SEAT MOTION REPRESENTATION

Pilot Position Acceleration Axis	Seatpan			Backrest			Lap belt
	Roll	Pitch	Heave	Pitch	Yaw	Fore-aft	X/Z
X		*		*		*	*
Y	*				*		*
Z			*				*
Roll	*				*		*
Pitch		*					
Yaw							

SOURCES: Albery et al., 1978; Bose et al., 1981; Kleinwaks, 1980.

of the ten kinds of motion information. The critical question is whether the representation of cues is adequate to support transport aircraft simulator motion requirements.

Quality of G-Seat Cueing

Design factors, experimental results, and user impressions formed the basis for assessing the ability of g-seats to deliver adequate motion cues in the three linear axes and in roll, those being the major motions experienced at the pilot position as a consequence of translational and rotational motion in the six axes at the aircraft cg.

Design Factors. At least four factors related to the design of g-seats introduce uncertainty about their ability to satisfy transport motion simulation requirements:

1. Lack of a lateral degree of freedom
2. Ambiguities in the presentation of cues
3. Drive algorithm uncertainties
4. Lack of vestibular onset cueing.

Table D.7

G-SEAT CUEING TO GENERATE TRANSPORT MOTION INFORMATION

Aircraft motion at center of gravity	Hydraulic Actuation							Pneumatic Actuation								Cue construction (see Tables D.5, D.6)	Predominant cueing axis at pilot position	Quality of cueing 1 = best 4 = worst
	Seatpan			Backrest			Lap Belt	Seatpan				Backrest						
	Roll	Pitch	Heave	Pitch	Yaw	Fore-aft	$\ddot{X}/\ddot{Y}$	Contour	Roll	Pitch	Heave	Contour	Pitch	Yaw	Fore-Aft			
Change in speed (accel/decel)		OS		OS		O	OS			S		S	S		S	$\ddot{X}$	Longitudinal-X	2
Uncoordinated Flight (yaw out of trim)	OS				OS		OS		S					S		$\ddot{Y}$	Lateral-Y	4
Change in pitch		OS	O				OS	S		S	S		S			$\ddot{Z}$ + pitch acc.	Vertical-Z	1
Change in roll	OS				OS		OS		S					S		roll acc.	Roll	3
Change in yaw	OS				OS		OS		S					S		$\ddot{Y}$	Lateral-Y	4
Buffet pitch			OS				OS									$\ddot{Z}$	Vertical-Z	1
Buffet roll	OS				OS		OS									roll acc.	Roll	3
Buffet yaw	OS				OS		OS									$\ddot{Y}$	Lateral-Y	4
Constant g-loading		OS	O				OS	S		S	S		S			$\ddot{Z}$ + pitch acc.	Vertical-Z	1
Constant deck angle		OS	O				OS	S		S	S		S			$\ddot{Z}$ + pitch acc.	Vertical-Z	1

O = motion used for onset cueing
S = motion used for sustained cueing
X/Y/Z = longitudinal/lateral/vertical axes
$\ddot{X}$ = longitudinal axis acceleration
$\ddot{Y}$ = lateral axis acceleration
$\ddot{Z}$ = vertical axis acceleration

Within their constrained excursion envelope, g-seats can to some extent move the pilot vertically, longitudinally, and in roll. They do not, however, move the pilot laterally, and consequently they must rely on other means to reproduce the force cues generated by yaw rotations about the aircraft cg. G-seats also cannot directly reproduce yaw rotations at the pilot position, although the backrests of some seats can rotate in yaw. Lacking a lateral degree of freedom, g-seats represent lateral accelerations by rolling the seatpan, yawing the seatback, and changing the tension of the lap belt. This calls into question the ability of the seat to provide the proper sensation a pilot would experience from a lateral acceleration, although as L. R. Young (1980b) properly points out: "It is recommended that in simulator design, emphasis be placed on obtaining perceptual fidelity rather than objective fidelity." In principle, then, the inability to represent accurately a lateral acceleration cue might not be very important. However, experimental results and other evidence to be presented later suggest otherwise.

The lack of a lateral degree of freedom also makes it more difficult for the g-seat to provide unambiguous cues for different motions. Tables D.5 and D.6 indicate that the g-seat uses the same axes to model roll and lateral motion. Hence one must question, for example, whether a pilot could use motion cues from a g-seat to evaluate whether he were properly executing a coordinated turn.

Uncertainty about how to effectively drive g-seats to generate satisfactory motion cues has remained a problem since their introduction. This problem existed with rudimentary bladder seats and has been compounded by the introduction of combined hydraulic/pneumatic seats. Algorithm development has usually come down to subjective evaluations by pilots concerning the realism of alternative cueing approaches (for example, see Bose et al., 1981; Kleinwaks, 1980; Showalter, 1978).

Designers, experimenters, and pilots express divergent viewpoints about what constitutes a satisfactory algorithm. Today there is no consensus on the proper cueing for even rudimentary maneuvers. For example, during a pull-up in an aircraft, the pilot sinks into the seat,

his lap belt loosens, and he senses the seat getting harder as g forces build up. To model this maneuver, some g-seat cueing algorithms inflate the seat cushion and tighten the lap belt; others, however, do exactly the reverse. With a hydraulic/pneumatic seat, some algorithms lower the seat pan while simultaneously inflating the seat cushion. Each of these approaches includes some counterintuitive cueing that is a by-product of the inherent design of the g-seat. Research is now under way at the most rudimentary level (i.e., one axis--roll, one drive--hydraulic, one task--roll stabilization) at the Air Force Aerospace Medical Research Laboratory to identify more effective algorithms (Levison et al., 1984; McMillan et al., 1984).

The bandwidth and response time of the hydraulic element of the g-seat indicates that it has the responsiveness to generate onset cues, but excursion limits constrain the ability of the seat to generate *vestibular onset cues*. For example, g-seats can generate 0.5 g in the heave direction. For a 0.04 g-sec vestibular threshold, the 0.5 g acceleration would have to be displayed for 0.08 seconds. A 4.5 inch displacement would be required to display and wash out the cue, 4.5 times the displacement of a typical g-seat. Moreover, this is just the displacement required to display a cue at the vestibular threshold, not anything more appreciable that might be experienced. There is not much latitude to improve the displacement capability of the g-seat, because the pilot's eye point must not be displaced much, and the seat cannot move the pilot's feet or hands off the controls in an unrealistic manner.

G-seats can provide some *sustained vestibular cues*. According to Young (1980b), the vestibular organs can detect tilts from the vertical of 1.5 to two degrees. G-seats can tilt 10 degrees or more, so reorientation of seatpans and backrests should provide some sustained vestibular cueing. The pneumatic part of the seat is, of course, designed to provide sustained haptic cueing.

The g-seat design, then, permits display of a partial set of motion cues the pilot experiences in the airplane, namely haptic onset cues and some sustained haptic and vestibular cues. A primary uncertainty associated with the use of the g-seat is the unknown consequence of not supplying vestibular onset cues. Young (1980b) sees an important role

for *both* haptic and vestibular cues: "Tactile cues respond most rapidly to changes in pressure, and signal any rapid changes in acceleration because of the consequent change in support force. They are the ideal first simulator cue for rapid onset." Young further states that "stimulation [of the vestibular organs is] . . . of principal interest for demonstrating and simulating sudden changes in linear or angular velocity [and is] . . . particularly important when early detection of aircraft acceleration is required to avoid instability or to react to critical failures."

Having a partial set of cues, primarily haptic, to work with in a simulator equipped only with a g-seat may be more critical for a transport aircraft application than for a fighter application because those kinds of cues simply are not as pronounced in a transport aircraft as they are in a fighter aircraft. As a consequence, the association between the haptic motion cue displayed in the simulator and that experienced in the airplane may be weaker, detracting from the training value of the simulator.

Experimental Results. A review of the literature and discussions with the simulator community identified 13 experiments evaluating how g-seats influenced pilot performance and the adequacy of alternative cueing algorithms, excluding in-house efforts by manufacturers to evaluate their designs (see Table D.8). None of the experiments directly answers the question of g-seat cueing adequacy for the C-17 simulator application. Of those 13 experiments, only two involved transport aircraft (10 involved fighters and one involved helicopters). We identified only three experiments, published or unpublished, that used hydraulic/pneumatic g-seats, and those experiments did not drive all hydraulic and pneumatic components of the seats.[3]

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[3]In evaluating a limited field-of-view visual system for the F-15 simulator, the Air Force used the hydraulic/pneumatic Goodyear g-seat, with all components operating, but because the objective of the experiment was to evaluate the visual display, no separate comparison was made of performance with the seat on and off, although it was observed that the g-seat cues distracted pilots and did not support the visual cues (O'Neal, 1984). Some of Goodyear's work on this same g-seat is described in Bose et al., 1981.

Table D.8

SUMMARY OF G-SEAT EXPERIMENTS

Organization	Aircraft type	Subjects	Equipment	Tasks	G-seat performance	References
NASA Langley (1983)	B-737	Test pilots	6-dof platform (VMS) NASA bladder g-seat Narrow FOV visual	VFR landing	Perf. with g-seat slightly better than no motion case. Perf. with g-seat *and platform no* better than platform alone. Perf. improvement observed with motion probably has little practical value.	Parrish and Steinmetz, 1983
NASA Ames (1980)	KC-135	Low and high time AF pilots	6-dof constrained FSAA Link bellows g-seat Narrow FOV visual	T/O with eng. failure Prec. turns Ldg. with wind shear	G-seat cueing had little overall effect on pilot perf. Some utility for tasks involving vertical acceleration cueing. Poor perf. for tasks requiring high frequency yaw and roll cues.	Showalter and Parris, 1980
NASA Langley (1977)	F-14	Test pilots	NASA DMS NASA bladder g-seat (normal acc. only) Wide FOV visual	Compensatory tracking of constant g turning tgt	G-seat allowed more precise control of aircraft.	Ashworth et al., 1977
NASA Langley (1980)	YF-16	Active F-15 pilots	6-dof platform (VMS) NASA bladder g-seat Narrow FOV visual	Compensatory tracking of constant g turning tgt	G-seat slightly reduced tracking errors.	McKissick et al., 1980
NASA Langley (1984)	F-16	Active F-15 pilots	6-dof platform (VMS) NASA bladder g-seat Narrow FOV visual	Compensatory tracking of constant g turning tgt	G-seat reduced tracking errors. Platform/seat combination performed best.	Ashworth et al., 1984
U. of Dayton Res. Inst. (1981)	F-16	Exp. fighter pilots	HRL-ASPT-motion off Link bellows g-seat NASA helmet loader G-suit Wide FOV visual	2 g pullup 4/6 g turns 2 g pushover	No reliable differences in g-seat and no motion case. Some degradation in perf. when g-seat added to g-suit or helmet loader.	Lee, 1981

Table D.8--continued

Organization	Aircraft type	Subjects	Equipment	Tasks	G-seat performance	References
AF HRL (1977)	T-37	T-37 instr. pilots	6-dof platform (ASPT) Link bellows g-seat Wide FOV visual	Takeoffs Ground contr. approaches 360 deg ohd pat. Slow flight Aileron roll	G-seat improved perf. on T/O and GCA maneuvers, those not involving significant roll and pitch axis rotations.	Irish et al., 1977
AF HRL (1978)	T-37	T-37 instr. pilots	6-dof platform (ASPT) Link bellows g-seat Wide FOV visual	GCA 360 deg ohd pat. Aileron roll Barrel roll Loop	G-seat had no significant effect on performance.	Irish and Buckland, 1979
NASA Ames (1978)	Fighter	Exp. F-4/105 pilots	Fixed base sim. Link bellows g-seat Narrow FOV visual	Pullout Pushover Level accel. S turns	Divergent pilot preferences for alternative g-cueing schemes. Maneuver influenced preference. Some satisfaction with vert. and long. axis cueing. G-seat's *potential* to generate hi-fidelity roll sensation limited.	Showalter, 1978
AF AMRL/ASD (?)	Fighter	NA	Hydr./Pneu. g-seat (ALCOGS-seatpan roll) Roll-Axis Tracking Sim. (RATS) Narrow FOV visual	Roll axis tracking	No perf. improvement in RATS of group previously trained in g-seat.	Unpublished
AF AMRL/ASD (1984)	Fighter	NA	ALCOGS-roll only RATS Narrow FOV visual	Roll axis tracking	G-seat tracking perf. better than no motion case, equal or better than RATS simulator.	McMillan et al., 1984; Levison, et al., 1984
Cranfield Inst. of Tech. (?)	T-33	Student, opnl., test pilots	3-dof platform Hydr. g-seat (normal acc. only) G-suit No visual	Head down terrain following	Performance slightly degraded with g-seat on.	Matthews and Martin, 1978
NTEC (1981)	LAMPS III helo.	Exp. helo. pilots	6-dof platform (VMS) NASA bladder g-seat (pitch, roll, long.) Narrow FOV visual Moving ship model	Stationkeeping with moving ship	G-seat reduced stationkeeping error by 5% over no motion case. Platform reduced error by 22%.	Ricard et al, 1981

Several findings recur across many of the experiments:

- The utility of the g-seat is very task-specific. G-seats provide better cueing for maneuvers that involve vertical and longitudinal accelerations, and poorer cueing for tasks involving roll and lateral accelerations.
- The choice of g-seat drive logic depends on the subjective and varying preferences of individual subjects and the maneuver being simulated.
- The g-seat's performance advantage over the no-motion case is usually modest.
- Motion platforms almost always show more performance improvement over the no-motion case than do g-seats.
- Evidence is mixed about the synergistic benefits derived from operating platforms and g-seats together.
- When given a choice, pilots generally express a preference for a motion platform over a g-seat.

The first finding noted above may partially explain why the g-seat has greater apparent utility for fighter applications than for transports. Fighters typically experience very pronounced sustained vertical axis accelerations (as high as 9 g) and to a lesser extent longitudinal axis accelerations (as high as 1.7 g) which create a very recognizable coupling between the pilot and the seat. The g-seat can reproduce some of the sensations of sustained-g maneuvers, and hence the pilot can associate the cues with sensations experienced in the aircraft. In contrast, transport aircraft accelerations in these axes are of much lower magnitudes and duration and the coupling between the pilot and his seat is much less pronounced. Hence there is not so strong an association of the g-seat stimuli with the transport aircraft.

The NASA Ames KC-135 experiment (Showalter and Parris, 1980) provides some insights about the comparative capabilities of g-seats and motion platform systems for transport aircraft simulation:

"In all three tasks, [takeoff with engine failure, precision turns, landing with wind shear] the presence of motion system cueing consistently improved performance in some manner . . . always accounting for far more variance than the g-seat factor."

"The presence or absence of g-seat cueing apparently had relatively little overall effect on pilot performance across tasks."

"On tasks [that require the pilot to perceive and effectively use high-frequency roll and yaw cues] . . . motion cueing promoted significantly better performance than g-seat cueing."

"The type of task affects the relative utility of g-seat and motion system cueing. . . . Tasks involving rapid and substantial changes in roll and yaw are best performed in a motion-based simulator without a g-seat, whereas those tasks composed of slow expected changes in bank angle, pitch, and z-axis velocities can be performed adequately by experienced pilots in either motion-based or g-seat-equipped simulators."

"Due to the design features of large-cabin aircraft, many emergency maneuvers . . . involve rapid changes in aircraft bank, yaw, and cockpit lateral position, thus making g-seat cueing less appropriate than motion system cueing."

"On an overall basis, the most useful large-cabin aircraft simulator is a motion-equipped one."

An earlier NASA Ames study (Showalter, 1978) had specifically evaluated alternative g-seat cueing schemes for several maneuvers and also came to the conclusion that the g-seat had greater utility for vertical and longitudinal axis cueing, but had great difficulty providing satisfying roll cues:

"It appears that the G-seat's potential to generate high-fidelity roll sensation is limited, partly because for normal roll rates, there appears [sic] to be very, very few noticeable roll specific seat contour changes."

"Given a lack of roll specific seat contours for normal roll rates and the inability of the G-seat to generate the significant cues of a rapid roll maneuver (i.e., upper body tilt), apparently the G-seat cannot induce the roll illusion."

"Given a situation in which the pilot is seated many feet from the aircraft's center of gravity, G-seat pitch cues may be no different than those for Z accelerations and, therefore practical."

"Cueing schemes for lateral accelerations (Y) and yaw may be as difficult to implement as a roll cueing scheme. In flight, Y and yaw accelerations generate some lateral body movement, which would be difficult to create with G-seat stimuli. Only some type of seat pan tilt and/or seat back rotation could be generated, and such stimuli would not cause the appropriate lateral body motion cue."

"In its present form the G-seat does not provide the upper body lateral pressure or position information necessary for roll or acceleration cueing."

Many of the observations noted above seem to result from the inherent mechanical design limitations of the g-seat that prevent it from inducing appropriate motion illusions rather than from the poor frequency response of the pneumatic bellows seat used in both experiments. We did, however, look beyond these experiments for evidence of better performance when using g-seats having better frequency response. The NASA bladder seat used in the helicopter experiment noted in Table D.8 has much better frequency response than the bellows seat and was driven in the roll, pitch, and longitudinal

axes (Ricard et al., 1981). That experiment showed a modest reduction (5 percent) in the helicopter stationkeeping error when using the seat as compared with the fixed base case. Similarly, continuing experiments at AF AMRL using the ALCOGS hydraulically-driven seatpan in roll show reductions in tracking error (as great as 45 percent) over the fixed base case when pilots tried to maintain a zero roll angle in the presence of turbulence (Levison et al., 1984; McMillan et al., 1984). The latter two experiments suggest that while much remains to be learned about g-seat cueing algorithms, it may be possible to improve the quality of roll cueing in contemporary g-seat designs. Given the experimental results that have been demonstrated thus far, there appears to be no reason for similar optimism about the ability of g-seats to provide high-fidelity lateral acceleration cues.

User Impressions. Discussions with a number of Air Force fighter pilots indicated a very low level of acceptance for g-seats. However, much of this negative view about g-seats may be a product of the simulator environment within which they are used. No operational F-15 simulator has a visual display, comparatively few A-10 simulators have visual displays, and these A-10 simulators are of very limited capability. Hence, in the absence of good visual displays, the simulators are often merely used to practice procedures and for instrument flight--and these activities are not characterized by the violent control inputs fighter pilots make in combat. Therefore, the g-seats in these simulators are not called upon today to provide pronounced motion cues and consequently have comparatively little effect on the pilot.

Pilots also believe a good visual display is needed to correlate the motion cues that are a consequence of significant control inputs. In the absence of that display, g-seat cues are simply not meaningful, and are at times a distraction.

Some substantiation that pilots cross-correlate g-seat cues with visual cues was provided in the Goodyear/Rediffusion demonstration of a limited field-of-view visual display in the F-15 simulator (O'Neal, 1984). With the visual display, a majority of the pilots participating in the evaluation almost immediately noted that g-seat motion cues, developed in a no-visual environment, did not agree with the visual scene and the way they knew the aircraft behaved. Some exploratory

software patches to the cueing algorithms performed off-line from the experiment convinced one senior pilot that the g-seat could be an asset with proper programming when complemented by a visual display. This demonstration reinforced experimental results that suggest the comparatively better cueing of the g-seat in the vertical and longitudinal axes and the poorer cueing in the roll and lateral axes. Other cueing experiments, however, have demonstrated the difficulty of achieving a significant degree of universality among pilots about the adequacy of particular cueing algorithms for g-seats (Showalter, 1978).

Observations Concerning G-Seats

This review of g-seat fidelity suggests that the g-seat does not achieve the motion-cueing fidelity of a motion platform for transport aircraft simulation. There is some evidence, both from objective experiments and from subjective impressions of users, that g-seats can provide some measure of cueing in the vertical and longitudinal axes. Experiments are still under way to determine the roll-axis cueing potential of the newer, more capable g-seats. Some early results examining one limited piloting task suggest that roll-axis cueing using a hydraulically-driven seatpan might improve performance over a fixed base simulation. The inherent design characteristics of g-seats appear to constrain severely their ability to reproduce adequate lateral acceleration cues--cues that are particularly important in recognizing and recovering from transport aircraft emergencies.[4]

COMPARATIVE ADEQUACY OF MOTION-CUEING ALTERNATIVES

A motion platform and a hydraulic/pneumatic g-seat appear to be the only alternatives that can potentially satisfy the C-17 simulator's motion requirements. For transport aircraft applications, the motion platform can supply adequate cues in all six degrees of freedom, and these cues appear qualitatively better than those supplied by the g-seat. The g-seat's cueing capabilities are particularly suspect with regard to representing roll, lateral, and yaw accelerations.

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[4]The rightmost column in Table D.7 summarizes this assessment in terms of the ability of the g-seat to generate each of the motion cues transport pilots typically use.

The assessment methodology used to compare C-17 simulator alternatives (see Appendix E) requires a binary rating of "adequate" or "inadequate" with respect to a particular alternative's ability to deliver each kind of motion cueing information used by transport pilots. Accordingly, Table D.9 displays the assumptions concerning motion cueing adequacy based on our review of design characteristics, experimental results, and user impressions. The "reference" g-seat serves as a baseline for our study. The "pessimistic g-seat" reflects uncertainty associated with the g-seat's roll cueing; it thus shows the sensitivity of the results to a lack of adequate cueing in that axis. The "incredible g-seat" is also displayed, but it is exceedingly unlikely that any g-seat could ever adequately provide *all* types of motion information typically used by transport pilots.

Although the results of this assessment are thought to be generally applicable to most large military aircraft, other types of aircraft could have appreciably different motion cueing requirements. Different aircraft characteristics, aircraft missions, motion cues associated with the maneuvers used to accomplish those missions, the population of subjects being trained, and the training objectives for the simulator each influence simulator motion needs. Those needs must be measured against the strengths and weaknesses of particular force cueing alternatives before drawing conclusions about the adequacy of each alternative.

Table D.9

ADEQUACY OF MOTION INFORMATION FROM ALTERNATIVE MOTION-CUEING DEVICES
(A = Adequate)

Type of Motion Information	Six-dof Platform	"Pessimistic" G-Seat	"Reference" G-Seat	"Incredible" G-Seat
Constant g-loading	A	A	A	A
Constant deck angle	A	A	A	A
Change in pitch	A	A	A	A
Buffet in pitch	A	A	A	A
Change in speed (accel/decel)	A	A	A	A
Change in roll	A		A	A
Buffet roll	A		A	A
Uncoordinated flight (yaw out of trim)	A			A
Change in yaw	A			A
Buffet yaw	A			A

Appendix E

METHODOLOGY FOR ASSESSING THE TRAINING CAPABILITY OF SIMULATORS

by

B. F. Goeller, L. M. Jamison, and R. J. Kaplan

SIMULATOR TRAINING CAPABILITY

Before we can describe our methodology for assessing the training capability of simulators, we must define this capability and explain why we want to assess it.

Figure E.1 shows the simulator's role in pilot training for a particular simulator design concept; the arrows indicate the direct influence of one factor on another during the training process.[1] The characteristics of the simulator design concept and the features of the C-17 determine *simulator fidelity*, the extent to which the simulator can provide an adequate representation of the different cues a pilot gets from the aircraft.[2]

Simulator training capability, which strongly depends on simulator fidelity, indicates what training a simulator *could* do--that is, the potential training tasks and conditions it could train personnel to perform.

Ideally, we would like to assess a si lator's training benefit in terms of its contribution to a pilot's overall proficiency in the aircraft. But this is impossible to do for several reasons. For one thing, we currently lack both the C-17 and its training syllabus. In addition, transfer of training can never be tested for some tasks that

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[1]To help keep the diagram simple, the influence of the instructor was omitted. It would parallel that of the pilot.

[2]Each type of information an aircrew uses to initiate or perform a flight task is called a *cue* for the task. See Appendix D and subsequent descriptions in this section.

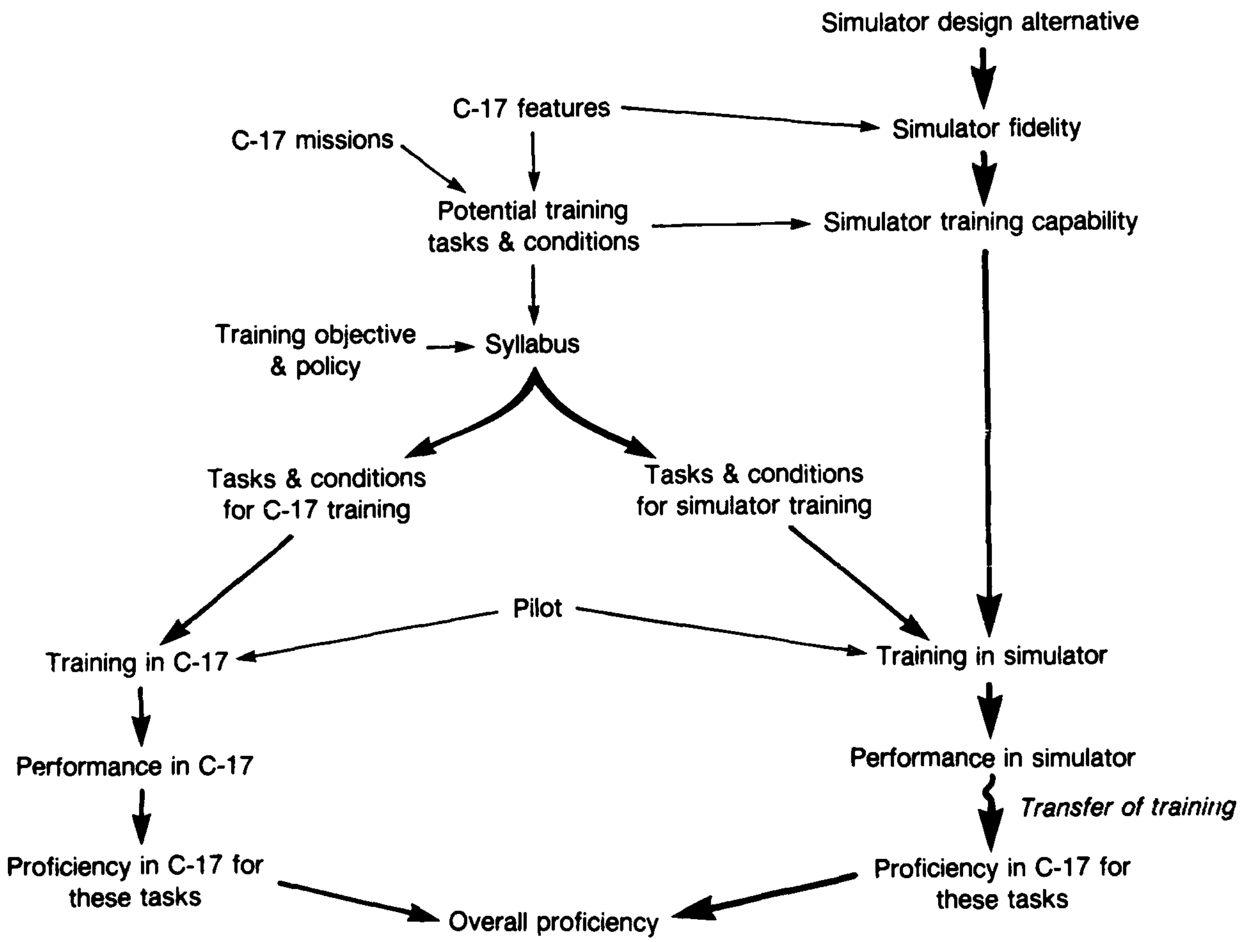

Fig. E.1 -- Simulator's role in pilot training

are not prudent to perform in the aircraft. But most important, transfer of training is difficult, if not impossible, to substantiate by experiment (see Appendix A).

Problems in Measuring the Transfer of Training

The object of any training is to bring individuals to a desired level of skill and proficiency easily, quickly, and at a minimum cost. The trade-offs among ease, speed, and cost of training must consequently consider the complex interactions of the engineering design, hardware practicality, software implementation, and the curriculum forming the training requirement. The measurement of the degree of skill attained and the rate at which training progresses is made by a combination of objective and subjective means, a major portion of which is usually the evaluation of the instructor. Evaluations of performance are made both in the simulator and in the aircraft.

The process of turning a novice into an experienced pilot is complex. It involves many years, dozens of instructors, countless pieces of study and reference material, and numerous devices, the most critical of which is the aircraft itself. This project has been concerned with a single aspect of this entire process, namely the presence or absence of a motion platform on the flight simulator, and it has attempted to evaluate the contribution of this feature on a training device to the entire chain of events. The question at the outset was whether there was a reasonable chance of succeeding in this endeavor.

In speaking to the many researchers in the human factors areas the answer appeared to be that, at least on a purely scientific basis, we could not succeed. It was not so much that the empirical evidence was nonexistent or insufficient, but rather that the experimental methodology was not up to a task of this magnitude. The number of variables to be held constant, or whose covariance would have to be removed, was large enough to make the experimental designs prohibitively expensive. The Human Resources Laboratory at Williams AFB designed what they considered to be the decisive experiment, but it was not carried out on the grounds that its cost was too high.

One would like to know if a subject trained in a simulator with a motion platform (when compared with his counterpart trained in a simulator without a motion platform) shows greater skill in flying an aircraft after training. This is a very difficult phenomenon to demonstrate since differences in pilot skill by the time they reach that

point in their careers is ver; small. Some researchers have gone so far as to say that one should not search for the effects of transfer of training; rather, one should look for the total cost and time involved in the whole training process with and without a motion platform.

Research problems are further complicated by the fact that early work on the effects of motion was performed using very bad motion platforms, ones in which the time lags between the initiation of an action that should produce motion and the motion itself were much too long to be realistic (see Appendix A). This early work produced negative findings concerning motion and helped support the belief that "bad motion is worse than no motion at all." Unfortunately, subsequent improvements in motion platforms have not been accompanied by similar studies.

In light of these problems, estimating the training capability of a simulator alternative seems the best practical way of assessing its training benefit.

Indexes of Simulator Training Capability

Training capability measures the number of potential flight tasks and conditions that are trainable in a particular simulator. So the definition of "trainable" is central to our methodology. A task or condition is properly *trainable* in a simulator alternative if and only if

1. The simulator provides all the onset and feedback cues the pilot requires,[3] and
2. Every cue comes from its main (primary) source.

If either of these criteria is violated, the pilot is being trained to perform the task differently in the simulator than he would in the aircraft. Violation of the first criterion means that the pilot does not receive some cue he requires in the aircraft. Violation of the

[3]This criterion does not include monitoring cues because information in this role is not important to the initiation or control of flight tasks. We thus ignore monitoring cues in our assessments. Definitions of the various types of cues appear later in this section.

second criterion means that the information for some cue is not being supplied from its main source, as it would be in the aircraft, but rather from some less important, substitute source.

We use several indexes of training capability to compare alternative simulator design concepts. The main index is the number of trainable tasks. Other indexes are the number of trainable variations on the tasks, one where the variations come from different types of environmental conditions and another where they come from different types of combat conditions.[4]

By considering the suitability of training potential tasks and conditions in the aircraft and the adequacy of cues provided by a particular alternative simulator concept, we can use these indexes to assess the simulator's training capability in terms of the number of potential tasks and conditions that are (1) not trainable in either the simulator or aircraft, (2) trainable only in the heavily-utilized aircraft, and (3) trainable only in the simulator, for reasons of prudence or difficulty.

These indexes also can be interpreted as proxies for the simulator's capability to meet various USAF objectives:

1. Improve safety-of-flight by permitting tasks and conditions to be trained in the simulator that are not prudent in the aircraft;
2. Enhance combat mission effectiveness and survival by providing more environmental and combat conditions for training;
3. Save aircraft time previously spent training routine tasks, thereby making more time available for combat training in the aircraft;[5] and

[4]In principle, we could also consider variations from combinations of different types of environmental and combat conditions.

[5]The USAF Scientific Advisory Board stated the following: "If MAC conducted all non-combat C-130 training in simulators, it would free 10,000 hours per year for combat training in the aircraft." *Report of the USAF Scientific Advisory Board Ad Hoc Committee on Simulation Technology,* 1978.

4. Ensure training system flexibility to handle changing operational concepts or syllabi and to tailor training to special missions.

The potential capability of a simulator concept to meet a particular objective can best be assessed by focusing on a particular subset of the potential tasks and conditions. For the first objective, the focus would be malfunction tasks and environmental conditions; for the second objective, it would be combat mission tasks and additional maneuvers unique to the C-17; for the third objective it would be basic and additional maneuver tasks; and for the fourth objective it would be all tasks and conditions.

DEFINITIONS

Before describing our procedure for calculating different indexes of training capability, we must first explain how we define such ingredients as missions, flight tasks, cues, conditions and task variations, and suitability.

C-17 Missions

The objective of C-17 missions, and all airlift missions, is the timely delivery of troops, equipment, units, and supplies. Delivery is accomplished by airland, airdrop, or extraction.[6] The C-17 is programmed to replace C-141s and many C-130s gradually over a number of years and will assume the missions of these aircraft. It will perform intercontinental logistics flights in peace and war as the C-141 does today and intratheater flights in a tactical environment as the C-130 does. The C-17 will also perform direct delivery flights from main operating bases, flying an intercontinental leg if necessary, and deliver its payload to forward operating locations (FOLs) or small austere airfields (SAAFs). Figure E.2 displays a pictorial view of these missions.

[6]Department of the Air Force, *U.S. Air Force Airlift Master Plan*, 1983.

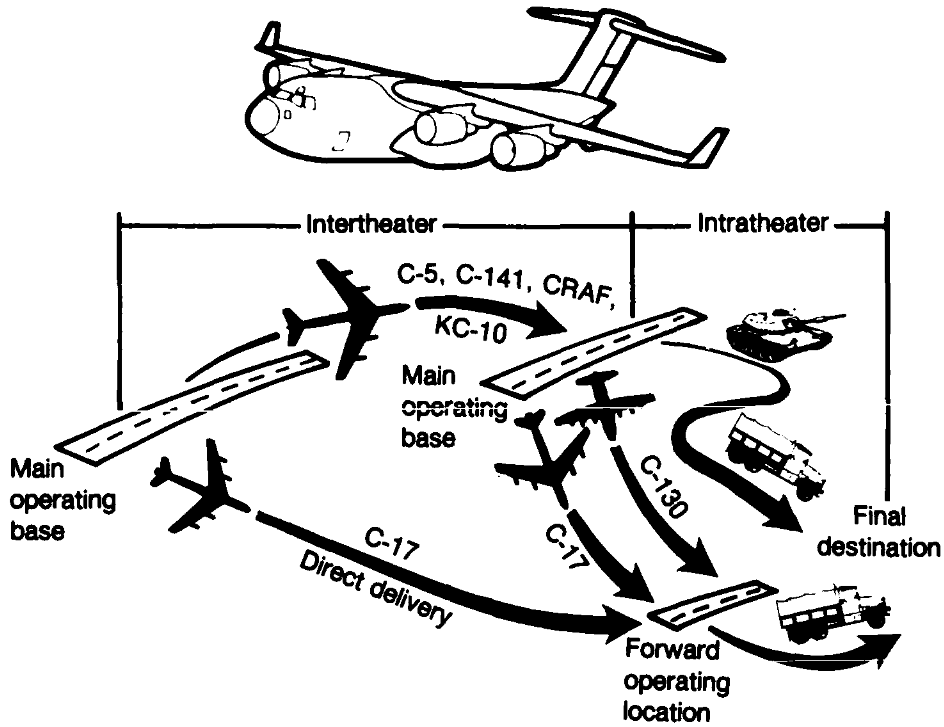

Fig. E.2 -- Airlift concept of operations

Table E.1 shows the C-17's major peacetime missions as drawn from the operational mission profiles.[7] Of these missions, 55 percent are consumed by local training, joint airborne and air transportability training (JAATT), and operational readiness inspections (ORI). These missions are devoted primarily to training and evaluating performance of such warfighting tasks as air refueling, low-level navigation, and delivery of troops and equipment by air drops, extractions, and assault landings at SAAFs.

An analysis of the expected mission profiles for the lifetime of the C-17 shows a high demand for difficult tasks flown near the ground (see Table E.2). In addition, C-17s will perform 3,950 hours of low-level cruise during turbulent air operations. It should be noted that

[7]See *System Specification for C-17 Airlift System*, Specification MDC S001, April 1, 1983.

Table E.1

ANTICIPATED ALLOCATION OF C-17 PEACETIME MISSIONS

Types of Missions	Percent of Flying Hours
Local Training	32
JAATT (Joint Airborne and Air Transportability Training)	17
ORI (Operational Readiness Inspection)	6
Logistics	45

SOURCE: *System Specification for C-17 Airlift System*, Specification MDC S001, April 1, 1983, p. 10-3.

Table E.2

SOME FLIGHT TASKS ANTICIPATED IN A C-17 AIRCRAFT LIFETIME

Tasks	Number
Turbulent Air Operations	
Air Refueling	758
Air Drops	497
Ground Operations at Main Bases	
Landings	11,291
Touch and Go's	3,674
Ground Operations at Small Austere Airfields	
Landings	3,026[a]
Touch and Go's	918
LAPES Maneuvers	1,617
LAPES Drops	213

[a]Of these landings, 276 will be with heavy-weight loads, 994 with medium-weight loads, and 1756 with light-weight loads.

SOURCE: *System Specification for C-17 Airlift System*, Specification MDC S001, April 1, 1983, p. 10-3.

few heavy-weight landings, performed primarily in ORIs, and LAPES drops are available to aircrew training. The demands of these training missions are reflected in the selection of flying tasks that were considered in our analysis.

Flight Tasks

In developing our list of *flight tasks*, we aimed at determining a minimum set that represented the full spectrum of hundreds of tasks that aircrews will perform. A training syllabus for the C-17, which would have a complete list of tasks, has not been developed. As a substitute, we used as a basis the primary tasks of civilian transport pilots and C-141 and C-130 aircrews in peacetime and warfighting situations. To these we added tasks unique to the C-17.[8]

Tasks were divided into four categories: basic, additional maneuvers, malfunctions, and mission. The 25 basic tasks listed in a DOT/FAA Report[9] were adopted in their entirety since they represent the major tasks of instrument and proficiency checks in any type of transport aircraft. The additional maneuvers in the DOT/FAA Report were amended to include C-17-unique tasks, such as DLC spoiler extension/retraction.[10] Excluding one task that did not apply to the C-17, our list includes 19 additional maneuver tasks relevant to the C-17. These are shown with the basic tasks and the reference sources for tasks in Table E.3. Using the DOT/FAA Report as a basis, a list of malfunction tasks appropriate to the C-17 was also developed. The C-130 training syllabus and a C-141 pilot tasks and objective training document[11] were examined

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[8]Various missions and aircrew tasks are discussed throughout *Prime Item Development Specification for C-17A Air Vehicle*, Part 1, Vol. 2, 1983.

[9]Gilliom et al., 1984.

[10]See category flight phase tasks (pp. 50-1, 50-2) and airplane failure states (p. 50-11) in *Prime Item Development Specification for C-17A Air Vehicle*, 1983.

[11]See the training syllabus and tactical operations in Air Force regulations and manuals in the 51-130 and 55-130 series and the *Tasks and Objective Document (TOD) for C-141 Pilots (Draft)*, Headquarters MAC, Undated.

Table E.3

FLIGHT TASKS AND SOURCES FOR TASKS FOR C-17 AIRCREWS:
BASIC AND ADDITIONAL MANEUVERS TASKS

Basic Task			Source of Task
Taxi	1	Taxi to takeoff position	1
	2	Taxi to gate	1
Takeoff	3	Takeoff ground roll	1
	4	Rotation	1
	5	Climb to airfoil clean up	1
	6	Airfoil clean up	1
	7	Reject takeoff	1
Area departure	8	Climb to cruise altitude	1
	9	Level off at cruise altitude	1
	10	Holding-Departure	1
Cruise	11	Cruise	1
Area arrival	12	Arrival descent	1
	13	Level-off	1
Emergency descent	14	Emergency descent	1
	15	Emergency level-off	1
Approach	16	Visual approach to visual glidepath	1
	17	Instrument approach to visual glidepath circling to visual transition	1
	18	Circling-to-land maneuver	1
	19	Missed approach	1
	20	Visual glidepath to LMTP (landing maneuver transition point)	1
Landing	21	LMPT to flare point	1
	22	Flare to initial touchdown	1
	23	Initial touchdown to start ground roll	1
	24	Landing ground roll	1
	25	Reject landing	1

Additional Maneuvers		Source of Task
1	Level turns w/roll in/roll out	1
2	Climbing turns w/roll in/roll out	1
3	Descending turns w/roll in/roll out	1
4	Climbs	1
5	Descents	1
6	Steep turns	1
7	Dutch roll	1
8	Recovery from imminent stalls	1,3
9	Gear extension/retraction	1
10	Speed brake extension/retraction	1,6
11	Flap/slat extension/retraction	1
12	Recognition of excessive pitch	1
13	Recognition of excessive bank	1
14	Recovery from excessive pitch	1
15	Recovery from excessive bank	1
16	In-flight thrust reversing	4
17	DLC spoiler extention/retraction	2
18	STOL landing	2,3
19	Air defense avoidance (jinking)	5
20	Ditching	3

SOURCE OF TASK:
1 DOT/FAA Report (Gilliom et al., 1984); task descriptions in Appendix A of the DOT/FAA Report.
2 Douglas Aircraft Co.
3 AFR 51-13D and AFR 55-130 series.
4 Tasks and Objective Document (TOD) for C-141 Pilots (Draft), Hq. MAC undated.
5 Rand.
6 Not applicable to the C-17.

to ascertain malfunctions associated with tactical operations, such as ditching. The experience of Dutch roll in the YC-15 flight tests[12] reinforced the retention of that DOT/FAA Report maneuver as a malfunction as listed in the DOT/FAA Report. Coping with aerodynamic distortion (battle damage) is listed as a malfunction; however, because of the variety of conditions that could exist and the overlap with other malfunctions of aircraft systems already listed, battle damage has been treated not as a task but as a combat condition explained below. There are 23 malfunctions in our list.

Combat mission tasks were developed from a combination of tactical tasks listed in the Douglas document and from current C-130 tactical tasks. The malfunction tasks and the nine combat mission tasks are shown in Table E.4. This study addressed a total of 76 flight tasks.

Cues

The types of information that an aircrew uses to initiate or perform a task are called the *cues* for that task. We analyzed the real-world cues provided to aircrews in aircraft while performing each of our 76 tasks using the methodology and some of the findings of the DOT/FAA Report as a starting point for our analysis. Our concentration was on motion (or force) cues;[13] however, visual, aural, and instrument cues were also considered when applicable. As we considered each task, and later each task-condition combination discussed below, we started by using the DOT/FAA methodology that involved three steps:

1. Prioritization of types of motion used in performing the 25 basic tasks under normal conditions of flight;
2. Revisions of these priorities as required for additional maneuvers and malfunctions that could accompany the basic tasks; and

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[12]Wood et al., 1977.

[13]The DOT/FAA Report defines "force cues" as all direct perceptions of motion arising from applications of physical force on body tissues.

Table E.4

FLIGHT TASKS AND SOURCES FOR TASKS FOR C-17 AIRCREWS:
MALFUNCTIONS AND MISSION TASKS

		Malfunctions	Source of Task		Mission Tasks	Source of Task
General	1	SCAS failures	2	1	Back taxiing	3
	2	One engine fails in flight	1	2	Low alt. parachute extract sys (LAPES)*	2,3
	3	Two engines fail		3	Close formation (FF)*	2,3
	4	Single hydraulic system fails	1,2			
	5	Any two hydraulic systems fail	1,2	4	Low-altitude cruise (LAC)*	2,3
	6	Spoiler system failures	2	5	In-flight refueling (RR)*	2,3
	7	Elevator system failures	2			
	8	Aileron system failures	2	6	Aerial delivery (AD)*	2,3
	9	Rudder system failures	2			
	10	Thrust reverser failures in-flight	2	7	Assault landing (STOL)*	2,3
	11	Asymmetric/split trailing edge (TE) flaps	1	8	STOL takeoff	3
	12	Asymmetric leading edge (LE) devices				
	13	Flaps (TE/LE) devices fail to extend/retract	1,2			
	14	Gear extends partially	1			
	15	Antiskid fails	1			
	16	Brakes fail	1			
	17	Loss of nose wheel steering	3			
	18	Nose wheel shimmy	1			
	19	No reverse (one engine) on landing	1			
	20	Tire failure	1			
	21	One engine fails on rotation	5			
Mission	22	Air refueling breakaway	3,5			
	23	Air drop extraction failure	3,5			

SOURCES: Rand analysis; MAC Hq interviewees.
SOURCE OF TASK:
1 DOT/FAA Report (Gilliom et al., 1984); task descriptions in App. A of the DOT/FAA Report.
2 Douglas Aircraft Co.
3 AFR 51-13D and AFR 55-130 series.
4 Tasks and Objective Document (TOD) for C-141 Pilots (Draft), Hq MAC, undated.
5 Rand.
*MAC acronyms.

3. Identification of environmental conditions that could affect the types of information.[14]

We employed the same techniques for analyzing the C-17-unique tasks, mission tasks, and combat conditions. Where the C-17 tasks were similar to the DOT/FAA tasks, we often adapted their results.

Types of Information. The following are the ten types of motion cues that were considered for each of the 25 basic tasks:

Change in speed	Buffet pitch
Uncoordinated flight (yaw out of trim)	Buffet roll
	Buffet yaw
Change in pitch	Constant G loading
Change in roll	Constant deck angle
Change in yaw	

Role and Priority of Cues. In flight, aircrews experience motion in many forms and realize this motion through the above types of information. Aircrews use the information in various *roles* depending on the task to be performed. The following are the roles and the symbols used to represent them:

Onset cue (C):	A signal required to initiate flight control inputs.
Feedback cue (F):	A signal required to regulate or refine flight control inputs.
Monitoring cue (M):	A signal required to confirm airplane status or the effects of control inputs when they do not require further refinements.

In the DOT/FAA study, three subject matter experts--all experienced air transport pilots--identified the *primary cueing role* of each of the ten types of information, if any, during the performance of each basic task. For each task, they then assigned the following *priorities* to each of its cues to indicate the *importance of motion among the all cue sources* (visual, motion, aural, and instruments) for that type of information for that task:[15]

[14]DOT/FAA Report, p. V-9.
[15]DOT/FAA Report, p. V-10.

Priority 1: Perceived physical movement is more important for cueing than any other source of information, such as instruments, sounds, or the external visual scene.
Priority 2: Perceived physical movement is an important cue, but other sources of information are more important.
Priority 3: Perceived physical movement is of no particular value to performing task.

Our study has incorporated the DOT/FAA assignment of cues and priorities for the basic tasks and for the additional maneuvers and malfunctions that are common between the B-727 transport addressed in the DOT/FAA study and any transport including the C-17. The Rand subject matter experts--two experienced pilots and a human factors expert--then assigned cues and priorities to the C-17-oriented tasks added by the Rand team. The Rand team reviewed all DOT/FAA entries and completed the entries for all added tasks, using the same rationale for cues and priorities and adapting cues of similar maneuvers.

Tables E.5 through E.8 display the cues and priorities for each set of tasks.

Conditions and Task Variations

Environmental Conditions. The environmental conditions that might reasonably be faced in flight tasks were introduced in the analysis, and the impact of these conditions on the cues for tasks was assessed for all 76 tasks. Each *task-condition combination* was considered to be a *variation of the task*. The categories of environmental conditions used in this study were identical to those used in the DOT/FAA Report:

Thunderstorms	Wind gusts
Ground effects	Wind shears
Ice on runway	Turbulence
Head wind	Engine icing
Tail wind	Airframe icing
Crosswind	

Each environmental condition affects one or more types of information received by pilots as they perform a task. Table E.9 shows the types of motion information affected by different categories of environmental conditions.

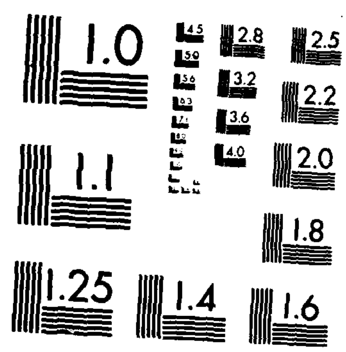
Table E.5

CUES FOR FLIGHT TASKS IN AIRCRAFT AND
MOTION'S IMPORTANCE AMONG CUE SOURCES: BASIC TASKS

BASIC TASKS			Change in speed	Uncoordinated flight	Change in pitch	Change in roll	Change in yaw	Buffet pitch	Buffet roll	Buffet yaw	Constant G loads'	Constant deck angle
			TYPES OF INFORMATION									
Taxi	1	Taxi to takeoff position	F2	F2	M3	M3	F2					
	2	Taxi to gate	F2	F2	M3	M3	F2					
Takeoff	3	Takeoff ground roll	F2	F2	M3	M3	F2					
	4	Rotation		F2	F2	M3	F2					M2
	5	Climb to airfoil clean up		C1	M3	F2	C1				M3	M2
	6	Airfoil clean up	M3	C1	F2	F2	C1	M2	M2	M2	M3	
	7	Reject takeoff	F2	F2	M3	M3	F2	M2	M2	M2		
Area Departure	8	Climb to cruise altitude		C1	F2	F2	C1				M3	M2
	9	Level off at cruise altitude		C1	F2	F2	C1				M3	M2
	10	Holding-Departure		C1	F2	F2	C1				M3	M3
Cruise	11	Cruise		C1	F2	F2	C1				M3	
Area Arrival	12	Arrival descent		C1	F2	F2	C1				M3	M2
	13	Level-off		C1	F2	F2	C1				M3	M2
Emergency descent	14	Emergency descent	M2	C1	F2	F2	C1	M2	M2	M2	M2	M2
	15	Emergency level-off	M3	C1	F2	F2	C1	M2	M2	M2	M2	M2
Approach	16	Visual approach to visual glidepath	M2	C1	F2	F2	C1	M2	M2	M2	M3	M2
	17	Instrument approach to visual glidepath circling to visual transition	M2	C1	C1	F2	C1	M2	M2	M2	M3	M2
	18	Circling-to-land maneuver		C1	F2	F2	C1	M2	M2	M2	M3	M2
	19	Missed approach	M2	C1	F2	F2	C1	M2	M2	M2	M3	M2
	20	Visual glidepath to LMTP (landing maneuver transition point)	M2	C1	F2	F2	C1	M2	M2	M2	M3	M2
Landing	21	LMPT to flare point		F2	F2	F2	F2	M3	M3	M3	M3	M2
	22	Flare to initial touchdown	M3	F2	F2	F2	F2				M2	M2
	23	Initial touchdown to start ground roll	M2	F2	F2	F2	F2				M3	M2
	24	Landing ground roll	F2	F2	M3	M3	F2	M2	M2	M2		
	25	Reject landing	M2	C1	F2	F2	C1	M2	M2	M2	M3	M2

SOURCE: DOT/FA Report (Gilliom et al., 1984).
CODES: C = onset cue; F = feedback cue; M = monitoring cue; 1, 2, and 3 = priority among cue sources.

AD-A174 745 ASSESSING THE BENEFITS AND COSTS OF MOTION FOR C-17 2/3
FLIGHT SIMULATORS: TECHNICAL APPENDIXES(U) RAND CORP
SANTA MONICA CA J R GEBMAN ET AL JUN 86
UNCLASSIFIED RAND/N-2301-AF F49620-86-C-0008 F/G 5/9 NL



CROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Table E.6

CUES FOR FLIGHT TASKS IN AIRCRAFT AND
MOTION'S IMPORTANCE AMONG CUE SOURCES: ADDITIONAL MANEUVERS

TYPES OF INFORMATION

	ADDITIONAL MANEUVERS	Change in speed	Uncoordinated flight	Change in pitch	Change in roll	Change in yaw	Buffet pitch	Buffet roll	Buffet yaw	Constant G loads	Constant deck angle
1	Level turns w/roll in/roll out		C1	F2	F2	C1				M3	
2	Climbing turns w/roll in/roll out		C1	F2	F2	C1				M3	M2
3	Descending turns w/roll in/roll out		C1	F2	F2	C1				M3	M2
4	Climbs		C1	F2	F2	C1				M3	M2
5	Descents		C1	F2	F2	C1				M3	M2
6	Steep turns		C1	F2	F2	C1				F2	
7	Dutch roll		C1	M3	F2	C1	M3	M3	M3	M3	
8	Recovery from imminent stalls	M3	C1	F2	F2	C1				M3	M3
9	Gear extension/retraction	M2		M3			M2	M2	M2		
10	Speed brake extension/retraction a	M2	C1	F2	F2	C1	F1	F1	F1		
11	Flap/slat extension/retraction	M2		C1	F2		M2	M2	M2		M2
12	Recognition of excessive pitch	M3		M3						M2	M2
13	Recognition of excessive bank		M2	M2	M2	M2				M2	
14	Recovery from excessive pitch	M3		F2						F2	F2
15	Recovery from excessive bank		M2	F2	F2	M2				F2	
16	In-flight thrust reversing	F1	C1	F2	F2	C1	F1	F1	F1		
17	DLC spoiler extention/retraction	M2	C1	C1	F2	C1	F1	F1	F1		
18	STOL landing		C1	F2	F2	C1	F2	F2	F1	M3	M2
19	Air defense avoidance (jinking)		C1	F2	F2	C1				F2	
20	Ditching	M2	C1	F2	F2	C1				M3	M2

SOURCES: DOT/FAA Report (Gilliom et al., 1984); Dougals Aircraft Co.; Rand analysis.
CODES: C = onset cue; F = feedback cue; M = monitoring cue; 1, 2, and 3 = priority among cue sources.

a Not applicable to C-17; DOT/FAA Report cues included for possible application to other aircraft

Table E.7

CUES FOR FLIGHT TASKS IN AIRCRAFT AND
MOTION'S IMPORTANCE AMONG CUE SOURCES: MALFUNCTIONS

MALFUNCTIONS		TYPES OF INFORMATION: Change in speed	Uncoordinated flight	Change in pitch	Change in roll	Change in yaw	Buffet pitch	Buffet roll	Buffet yaw	Constant G loads	Constant deck angle
General	1 SCAS failures a		C1	F1	F1	C1					
	2 One engine fails in flight b	C1	C1		F2	C1					
	3 Two engines fail	C1	C1	F2	F2	C1					
	4 Single hydraulic system fails c	F2		M2	F2		F2	F2	F2		
	5 Any two hydraulic systems fail c	F2	C1	M2	F2	C1	M3	M3	M3		
	6 Spoiler system failures d		F2		M3	F2	M3	M3	M3		
	7 Elevator system failures e		C1								
	8 Aileron system failures f		C1		F2	C1	M3	M3	M3		
	9 Rudder system failures g		C1			C1					
	10 Thrust reverser failures in-flight	M2	C1	F2	F2	C1	F1	F1	F1		
	11 Asymmetric/split trailing edge (TE) flaps	M2		C1	M3	M3	M2	M2	M2		M3
	12 Asymmetric leading edge (LE) devices	M3	C1	F2	C1	C1	M2	M2	M2		
	13 Flaps (TE/LE) devices fail h		C1	F2	F2	C1	F2	F2			
	14 Gear extends partially	M2	C1	M3	F2	C1	M2	M2	M2		
	15 Antiskid fails	F2	F2	M3	M3	F2	M2	M2	M2		
	16 Brakes fail	C1	F2	M3	M3	F2	M2	M2	M2		
	17 Loss of nose wheel steering i	F2	F2	M3	M3	F2					
	18 Nose wheel shimmy i	F2	F2	M3	M3	F2	C1				
	19 No reverse (one engine) on landing	F2	C1	M3	M3	C1					
	20 Tire failure	F2	F2	F2	F2	F2	M2	M2	M2		
	21 One engine fails on rotation b	C1	C1		F2	C1					
Mission	22 Air refueling breakaway	F2	C1	F2	F2	C1	M2	M2	M2		
	23 Air drop extraction failure	F2	C1	F2	F2	C1				F2	F2
	24 Aerodynamic distortion (battle damage) j	C1	C1	F2	F2	C1	F2	F2	F2		

SOURCES: DOT/FAA Report (Gilliom et al., 1984); Rand analysis; MAC Hq interviewees.
CODES: C = onset cue; F = feedback cue; M = monitoring cue; 1, 2, and 3 = priority among cue sources.

a Task is not counted when scenario has SCAS turned off.

b DOT/FAA's single task, one engine fails, has been changed to two tasks, 2 and 21. This change was made to reflect Air Force's policy to avoid the training of engine failures during critical flight maneuvers and to reflect the opinion of nearly all pilots we interviewed who mentioned engine failure at rotation as an event where motion cues were essential.

c-i Cues for these tasks are the same as for DOT/FAA's tasks: c-"A" hydro fails and total hydro failure; d-spoiler float; e-runaway stab trim; f-lower rudder limiter; g-yaw damper fails; h-airfoil cleanup; and i-landing roll.

j Cues are shown for this malfunction but task is not counted because the malfunction is treated as part of the battle damage condition.

Table E.8

CUES FOR FLIGHT TASKS IN AIRCRAFT AND
MOTION'S IMPORTANCE AMONG CUE SOURCES: MISSION TASKS

TYPES OF INFORMATION

MISSION TASKS		Change in speed	Uncoordinated flight	Change in pitch	Change in roll	Change in yaw	Buffet pitch	Buffet roll	Buffet yaw	Constant G loads	Constant deck angle
1 Back taxiing		F2	F2	M3	M3	F2					
2 Low alt. parachute extract sys	(LAPES)	M2	C1	F1	F2	C1	M2	M2	M2	M2	F1
3 Close formation	(FF)	F2	C1	F2	F2	C1	M2	M2	M2	F2 a	
4 Low altitude cruise	(LAC)		C1	F2	F2	C1				M3	
5 In-flight refueling	(RR)	F2	C1	F2	F2	C1	M2	M2	M2	M2	
6 Aerial delivery	(AD)	M2	C1	F1	F2	C1	M2	M2	M2	M2	
7 Assault landing	(STOL)	F2	C1	F2	F2	C1	F2 a	F2 a	F2 a	M2	M2
8 STOL takeoff		F2	C1	F2	F2	C1	M2	M2	M2	M3	M2
9 STOL go-around		F1	C1	F2	F2	C1	M2	M2	M2	M3	M2

SOURCES: Rand analysis; MAC Hq interviewees.
CODES: C = onset cue; F = feedback cue; M = monitoring cue; 1, 2, and 3 = priority among cue sources.

a These mission tasks are made up of component tasks. The type of cue specified for each type of information is based on the component task for which the information type is most important.

Table E.9

TYPES OF MOTION INFORMATION
AFFECTED BY GIVEN ENVIRONMENTAL CONDITIONS

ENVIRONMENTAL CONDITIONS	TYPES OF INFORMATION									
	Change in speed	Uncoordinated flight	Change in pitch	Change in roll	Change in yaw	Buffet pitch	Buffet roll	Buffet yaw	Constant G loads	Constant deck angle
Thunderstorms	V	V	V	V	V	V	V	V	V	V
Ground effects	V		V							
Ice on runway	V	V			V					
Head wind	V									
Tail wind	V									
Crosswind	V	V		V	V					
Wind gusts	V	V	V	V	V					
Wind shears	V	V	V	V	V	V	V	V		
Turbulence	V	V	V	V	V	V	V	V		
Engine icing	V									V
Airframe icing						V	V	V		V

SOURCE: DOT/FAA Report (Gilliom et al., 1984), p. E-5.
CODE: V = Type of information affected by an environmental condition.

Combat Conditions. Beside environmental conditions that affect all types of flying, the C-17 will be subject to flight in *combat conditions*. These conditions can affect flight tasks by imposing requirements for maneuvers and restraints to normal operations not demanded by environmental conditions. Therefore, the Rand team developed a second set of conditions that represented the broad spectrum of possible *warfighting environments*. Eleven potential categories of combat conditions were reduced to five after we conducted interviews with officers at Headquarters Military Airlift Command and the C-130 training course at Little Rock AFB, Arkansas.[16] These five categories of combat conditions are

Load conditions:	Gross weight, center of gravity
Obstructions:	Obstacles and terrain
Enemy activity:	SAMs and gunfire in low-level cruise and in drop/landing zones
Battle damage:	Aerodynamic distortion associated with systems malfunctions
Operating site characteristics:	Landing/takeoff surface, dimensions, slope, and condition

Suitability

The final set of factors used in our analysis was the *suitability* of a simulator or an aircraft to provide a means to train pilots for tasks under different conditions. Air Force policy on the use of ground-based training systems states the following:[17]

> "For aircrew training, training systems will be developed to complement aircraft training for safety-of-flight tasks and those combat tasks that are difficult to train in the aircraft because of equipment, range, or airspace limitations. MAJCOMs will tailor training systems to meet their requirements for initial and continuation training within the following capabilities:
> (1) Safety-of-flight training for those *tasks that require repetition or flight conditions that are difficult or not prudent to achieve in the aircraft* [italics added]. Normal, emergency,

[16]Col David Nelson and Lt Col Ronald Duke, Headquarters MAC, and Maj Michael Sieverding, 314 TAW, Little Rock AFB, Arkansas.

[17]See Air Force Regulation 50-11.

and instrument procedures as well as basic crew coordination are included in this category. . . ."

Using this Air Force policy guidance, we first specified the task-condition variations that our team thought were not reasonable training requirements. These included ground effects while taxiing and ice on the runway while in flight. Among the remaining variations, the team specified those they considered *not prudent* to be performed in an aircraft, such as outboard engine failure at rotation and maneuvers in thunderstorms, and those considered *too difficult* to perform in an aircraft, such as landing maneuvers in crosswind or gusts and taxiing on icy runways, because finding these conditions at desired times in a course of instruction can be difficult. In case of doubt as to *not prudent or too difficult* to be trained in an aircraft, a variation was classified as suitable to be trained in both simulator and aircraft.[18] Suitability for each task-condition variation was recorded using the following code:

- P Not prudent to train in aircraft.
- D Too difficult to train in aircraft, e.g., difficult to find environment, airspace, and ranges or too time consuming.
- X Not applicable: not applicable to task or task would not be performed in aircraft operational missions under condition.
- \+ Suitable for training in both simulator and aircraft.

The suitability code for each of the 76 tasks with normal flight conditions is shown in Tables E.10 and E.11 and in combination with different environmental conditions in Tables E.12 through E.15. Combat conditions were applied to the nine combat mission tasks only, and these suitability codes are shown in Table E.16. The contents of these tables were acceptable to officers in MAC Headquarters responsible for preparation of the C-17 training program.

DETERMINATION OF SIMULATOR TRAINING CAPABILITY

We now describe the procedures we developed for calculating each of the indexes of simulator training capability.

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[18]A particular simulator may not have the capability to provide the training but this issue was addressed separately.

Table E.10

SUITABILITY OF TASKS TO BE TRAINED
IN NORMAL CONDITIONS: BASIC AND ADDITIONAL TASKS

BASIC TASKS			SUITABILITY IN NORMAL CONDITIONS
Taxi	1	Taxi to takeoff position	+
	2	Taxi to gate	+
Takeoff	3	Takeoff ground roll	+
	4	Rotation	+
	5	Climb to airfoil clean up	+
	6	Airfoil clean up	+
	7	Reject takeoff	+
Area Departure	8	Climb to cruise altitude	+
	9	Level off at cruise altitude	+
	10	Holding-Departure	+
Cruise	11	Cruise	+
Area Arrival	12	Arrival descent	+
	13	Level-off	+
Emergency descent	14	Emergency descent	P
	15	Emergency level-off	D
Approach	16	Visual approach to visual glidepath	+
	17	Instrument approach to visual glidepath circling to visual transition	+
	18	Circling-to-land maneuver	+
	19	Missed approach	+
	20	Visual glidepath to LMTP	+
Landing	21	LMPT to flare point	+
	22	Flare to initial touchdown	+
	23	Initial touchdown to start ground roll	+
	24	Landing ground roll	+
	25	Reject landing	+

	ADDITIONAL MANEUVERS	SUITABILITY IN NORMAL CONDITIONS
1	Level turns w/roll in/roll out	+
2	Climbing turns w/roll in/roll out	+
3	Descending turns w/roll in/roll out	+
4	Climbs	+
5	Descents	+
6	Steep turns	+
7	Dutch roll	P/D
8	Recovery from imminent stalls	P
9	Gear extension/retraction	+
10	Speed brake extension/retraction	+*
11	Flap/slat extension/retraction	+
12	Recognition of excessive pitch	P
13	Recognition of excessive bank	P
14	Recovery from excessive pitch	P
15	Recovery from excessive bank	P
16	In-flight thrust reversing	+
17	DLC spoiler extention/retraction	+
18	STOL landing	+
19	Air defense avoidance (jinking)	+
20	Ditching	P/D

SOURCES: Rand analysis; MAC Hq interviewees.
SUITABILITY CODES:
P = not prudent to train in aircraft.
D = too difficult to train in aircraft, e.g., difficult to find environment, airspace, and ranges, or too time-consuming.
X = not applicable: not applicable to task or task would not be performed in aircraft operational missions under condition.
+ = trainable in both simulator and aircraft.
LMPT: Landing maneuver transition point.
*Not applicable to the C-17.

Table E.11

SUITABILITY OF TASKS TO BE TRAINED
IN NORMAL CONDITIONS: MALFUNCTIONS AND MISSION TASKS

MALFUNCTIONS		SUITABILITY IN NORMAL CONDITIONS	MISSION TASKS		SUITABILITY IN NORMAL CONDITIONS
General	1 SCAS failures	+	1	Back taxiing	+
	2 One engine fails in flight	+	2	Low alt. parachute extract sys(LAPES) *	+ 1
	3 Two engines fail	P	3	Close formation (FF) *	+
	4 Single hydraulic system fails	P	4	Low altitude cruise (LAC) *	+ 2
	5 Any two hydraulic systems fail	P	5	In-flight refueling (RR) *	+
	6 Spoiler system failures	P	6	Aerial delivery (AD) *	+
	7 Elevator system failures	P	7	Assault landing (STOL) *	+ 2
	8 Aileron system failures	P	8	STOL takeoff	+
	9 Rudder system failures	P	9	STOL go-around	+
	10 Thrust reverser failures in-flight	P			
	11 Asymmetric/split trailing edge (TE) flaps	P/D			
	12 Asymmetric *leading edge (LE) devices*	P/D			
	13 Flaps (TE/LE) devices fail to extend/retract	+			
	14 Gear extends partially	P/D			
	15 Antiskid fails	P			
	16 Brakes fail	P			
	17 Loss of nose wheel steering	P			
	18 Nose wheel shimmy	P/D			
	19 No reverse (one engine) on landing	+			
	20 Tire failure	D			
	21 One engine fails on rotation	P			
Mission	22 Air refueling breakaway	+			
	23 Air drop extraction failure	P/D			

SOURCES: Rand analysis; MAC Hq interviewees.
SUITABILITY CODES:
P = not prudent to train in aircraft.
D = too difficult to train in aircraft.
X = not applicable.
+ = trainable in both simulator and aircraft.
1 Not Prudent (P) if SCAS fails (Douglas test pilot).
2 Difficult (D) for stress on aircraft.
*MAC acronyms.

Table E.12

SUITABILITY OF DIFFERENT ENVIRONMENTAL CONDITIONS TYPES
TO TRAINING OF TASKS: BASIC TASKS

BASIC TASKS		Thunderstorms	Ground effects	Ice on runway	Head wind	Tail wind	Crosswind	Wind gusts	Wind shears	Turbulence	Engine icing	Airframe icing
		SUITABILITY BY TYPE OF ENVIRONMENTAL CONDITION										
Taxi	1 Taxi to takeoff position	P/D	X	D	X	X	X	D	X	X	X	X
	2 Taxi to gate	P/D	X	D	X	X	X	D	X	X	X	X
Takeoff	3 Takeoff ground roll	P/D	+	D	D	P	D	D	X	X	P/D	P/D
	4 Rotation	P/D	+	D	D	P	D	D	P	D	P/D	P/D
	5 Climb to airfoil clean up	P/D	+	X	X	X	X	X	P	D	P/D	P/D
	6 Airfoil clean up	P/D	+	X	X	X	X	D	P	D	P/D	P/D
	7 Reject takeoff	P/D	X	X	D	D	D	D	X	D	P/D	P/D
Area Departure	8 Climb to cruise altitude	P/D	X	X	D	D	D	X	X	D	P/D	P/D
	9 Level off at cruise altitude	P/D	X	X	X	X	X	X	X	D	P/D	P/D
	10 Holding-Departure	P/D	X	X	D	D	D	X	X	D	P/D	P/D
Cruise	11 Cruise	P/D	X	X	D	D	D	X	X	D	P/D	P/D
Area Arrival	12 Arrival descent	P/D	X	X	D	D	D	X	X	D	P/D	P/D
	13 Level-off	P/D	X	X	X	X	X	X	X	D	P/D	P/D
Emergency descent	14 Emergency descent	P/D	X	X	X	X	X	X	X	D	P/D	P/D
	15 Emergency level-off	P/D	X	X	X	X	X	X	X	D	P/D	P/D
Approach	16 Visual approach to visual glidepath	P/D	X	X	D	D	D	X	X	D	P/D	P/D
	17 Instrument approach to visual glidepath circling to visual transition	P/D	X	X	D	D	D	X	X	D	P/D	P/D
	18 Circling-to-land maneuver	P/D	X	X	D	D	D	X	P	D	P/D	P/D
	19 Missed approach	P/D	X	X	D	D	D	D	P	D	P/D	P/D
	20 Visual glidepath to LMTP	P/D	X	X	D	D	D	X	D	D	P/D	P/D
Landing	21 LMPT to flare point	P/D	+	X	D	D	D	D	D	D	P/D	P/D
	22 Flare to initial touchdown	P/D	+	X	D	D	D	D	P	D	P/D	P/D
	23 Initial touchdown to start ground roll	P/D	+	D	D	P	D	D	P	D	P/D	P/D
	24 Landing ground roll	P/D	X	D	D	P	D	D	X	X	P/D	P/D
	25 Reject Landing	P/D	X	X	X	D	D	D	X	D	P/D	P/D

SOURCES: Rand analysis; MAC Hq interviewees.
SUITABILITY CODES:
P = not prudent to train in aircraft.
D = too difficult to train in aircraft.
X = not applicable.
+ = trainable in both simulator and aircraft.
LMPT: Landing maneuver transition point.

Table E.13

SUITABILITY OF DIFFERENT ENVIRONMENTAL CONDITIONS TYPES
TO TRAINING OF TASKS: ADDITIONAL MANEUVERS

SUITABILITY BY TYPE OF ENVIRONMENTAL CONDITION

ADDITIONAL MANEUVERS	Thunderstorms	Ground effects	Ice on runway	Head wind	Tail wind	Crosswind	Wind gusts	Wind shears	Turbulence	Engine icing	Airframe icing
1 Level turns w/roll in/roll out	X	X	X	X	X	X	X	X	D	X	X
2 Climbing turns w/roll in/roll out	X	X	X	X	X	X	X	X	D	X	X
3 Descending turns w/roll in/roll out	X	X	X	X	X	X	X	X	D	X	X
4 Climbs	X	X	X	X	X	X	X	X	D	X	X
5 Descents	X	X	X	X	X	X	X	X	D	X	X
6 Steep turns	X	X	X	X	X	X	X	X	D	X	X
7 Dutch roll	X	X	X	X	X	X	X	X	D	X	X
8 Recovery from imminent stalls	X	X	X	X	X	X	P/D	P/D	P/D	P/D	P/D
9 Gear extension/retraction	X	X	X	X	X	X	X	X	X	X	X
10 Speed brake extension/retraction a	X	X	X	X	X	X	X	X	X	X	X
11 Flap/slat extension/retraction	X	X	X	X	X	X	X	X	X	X	X
12 Recognition of excessive pitch	X	X	X	X	X	X	X	X	X	X	X
13 Recognition of excessive bank	X	X	X	X	X	X	X	P/D	X	X	X
14 Recovery from excessive pitch	X	X	X	X	X	X	X	X	X	X	X
15 Recovery from excessive bank	X	X	X	X	X	X	X	P/D	P/D	X	X
16 In-flight thrust reversing	X	X	X	X	X	X	X	X	X	X	X
17 DLC spoiler extention/retraction	X	X	X	X	X	X	X	P/D	D	P/D	P/D
18 STOL landing	X	X	P/D	D	P/D	D	D	P	D	P/D	P/D
19 Air defense avoidance (jinking)	X	X	X	X	X	X	D	P/D	P/D	X	X
20 Ditching	X	P/D	X	P/D	P/D	P/D	P/D	X	X	X	X

SOURCES: Rand analysis; MAC Hq interviewees.
SUITABILITY CODES:
P = not prudent to train in aircraft.
D = too difficult to train in aircraft.
X = not applicable.
+ = trainable in both simulator and aircraft.

a Not applicable to C-17; DOT/FAA Report cues included for possible application to other aircraft.

Tab'e E.14

SUITABILITY OF DIFFERENT ENVIRONMENTAL CONDITIONS TYPES
TO TRAINING OF TASKS: MALFUNCTIONS

MALFUNCTIONS			SUITABILITY BY TYPE OF ENVIRONMENTAL CONDITION: Thunderstorms	Ground effects	Ice on runway	Head wind	Tail wind	Crosswind	Wind gusts	Wind shears	Turbulence	Engine icing	Airframe icing
General	1	SCAS failures a	X	P/D	X	D	P/D	D	D	X	P/D	X	X
							X	X	X	X	P/D	P/D	P/D
	2	One engine fails in flight	X	X	X	X	P/D	P/D	P/D	P/D	P/D	P/D	P/D
	3	Two engines fail	X	X	X	P/D	X	X	X	X	P/D	X	X
	4	Single hydraulic system fails	X	X	X	X	X	X	X	X	P/D	X	X
	5	Any two hydraulic systems fail	X	X	X	X	X	X	X	X	P/D	X	X
	6	Spoiler system failures	X	X	X	X	X	X	X	X	P/D	X	X
	7	Elevator system failures	X	X	X	X	X	X	X	X	P/D	X	X
	8	Aileron system failures	X	X	X	X	X	P/D	P/D	X	P/D	X	X
	9	Rudder system failures	X	X	X	X	X	P/D	P/D	X	P/D	X	X
	10	Thrust reverser failures in-flight	X	X	X	X	X	X	X	X	P/D	X	X
	11	Asymmetric/split trailing edge (TE) flaps	X	P/D	X	X	X	P/D	P/D	P/D	P/D	X	X
	12	Asymmetric leading edge (LE) devices	X	P/D	X	X	X	P/D	P/D	P/D	P/D	X	X
	13	Flaps (TE/LE) devices fail to extend/retract	X	+	X	+	P/D	P/D	P/D	P/D	P/D	X	X
	14	Gear extends partially	X	X	X	X	X	X	X	X	P/D	X	X
	15	Antiskid fails	X	X	P/D	P/D	P/D	P/D	P/D	X	X	X	X
	16	Brakes fail	X	X	P/D	P/D	P/D	P/D	P/D	X	X	X	X
	17	Loss of nose wheel steering	X	X	P/D	P/D	P/D	P/D	P/D	X	X	X	X
	18	Nose wheel shimmy	X	X	P/D	P/D	P/D	P/D	P/D	X	X	X	X
	19	No reverse (one engine) on landing	X	X	P/D	P/D	P/D	P/D	P/D	X	X	X	X
	20	Tire failure	X	X	P/D	P/D	P/D	P/D	P/D	X	X	X	X
	21	One engine fails on rotation	X	P	X	P/D	P/D	P/D	P/D	P/D	P/D	P/D	P/D
Special c	22	Air refueling breakaway	X	X	X	X	X	X	X	P/D	D	X	X
	23	Air drop extraction failure	X	X	X	X	X	X	X	P/D	P/D	X	X
	24	Aerodynamic distortion (battle damage) b	X	D	X	D	D	D	D	P/D	D	X	X

SOURCES: Rand analysis; MAC Hq interviewees.
SUITABILITY CODES:
P = not prudent to train in aircraft.
D = too difficult to train in aircraft.
X = not applicable.
+ = trainable in both simulator and aircraft.

a Task is not counted when scenario has SCAS turned off.

b Cues are shown for this malfunction but task is not counted because the malfunction is treated as part of the battle damage combat condition.

c Associated with mission tasks.

Table E.15

SUITABILITY OF DIFFERENT ENVIRONMENTAL CONDITIONS TYPES
TO TRAINING OF TASKS: MISSION TASKS

MISSION TASKS	Thunderstorms	Ground effects	Ice on runway	Head wind	Tail wind	Crosswind	Wind gusts	Wind shears	Turbulence	Engine icing	Airframe icing
	SUITABILITY BY TYPE OF ENVIRONMENTAL CONDITION										
1 Back taxiing	P/D	X	P/D	D	D	D	D	X	X	X	X
2 Low alt. parachute extract sys(LAPES)*	X	+	X	D	D	D	D	P/D	D	P/D	P/D
3 Close formation (FF)*	X	X	X	X	X	X	X	P/D	D	P/D	P/D
4 Low altitude cruise (LAC)*	X	X	X	D	D	D	X	P/D	D	P/D	P/D
5 In-flight refueling (RR)*	X	X	X	X	X	X	X	P/D	D	P/D	P/D
6 Aerial delivery (AD)*	X	X	X	D	D	D	X	P/D	D	P/D	P/D
7 Assault landing (STOL)*	X	+	P/D	D	D	D	D	P/D	D	P/D	P/D
8 STOL takeoff	X	+	P/D	D	D	D	D	P/D	D	P/D	P/D
9 STOL go-around	P/D	D	X	D	D	D	D	P/D	D	P/D	P/D

SOURCES: Rand analysis; MAC Hq interviewees.
SUITABILITY CODES:
P = not prudent to train in aircraft.
D = too difficult to train in aircraft.
X = not applicable.
+ = trainable in both simulator and aircraft.
*MAC acronyms.

Table E.16

SUITABILITY OF DIFFERENT COMBAT CONDITIONS TYPES
TO TRAINING OF TASKS: MISSION TASKS

MISSION TASKS		Load Conditions	Obstructions	Enemy Activity	Battle Damage	Operating Site Characteristics
1 Back taxiing		+	+	X	X	+
2 Low alt. parachute extract sys(LAPES) *		P	P	P/D	P	+
3 Close formation	(FF) *	P	+	P/D	P	X
4 Low altitude cruise	(LAC) *	P	+	X	P/D	X
5 In-flight refueling	(RR) *	+	X	X	X	X
6 Aerial delivery	(AD) *	+	P	X	P/D	+
7 Assault landing	(STOL) *	P	+	P/D	P	+
8 STOL takeoff		P	+	X	P/D	+
9 STOL go-around		+	+	+	P	+

Column group heading: TYPE OF COMBAT CONDITION

SOURCES: Rand analysis; MAC Hq interviewees.
SUITABILITY CODES:
P = not prudent to train in aircraft.
D = too difficult to train in aircraft.
X = not applicable.
+ = trainable in both simulator and aircraft.
*MAC acronyms.

Procedure for Counting Trainable Tasks

Figure E.3 shows the procedure for counting trainable tasks. The procedure begins by specifying a simulator design alternative to be analyzed. For our purposes, this conceptual alternative need be described only by its fidelity; that is, the extent to which it can provide an adequate representation of the different types of information (cues) the pilot gets from the aircraft. Because all simulator alternatives considered in this study provide adequate visual, instrument, and aural cues, we need concern ourselves only with an alternative's motion fidelity. Table E.17 shows the adequacy of ten types of motion information provided by different simulator alternatives.

The procedure described in Fig. E.3 picks the next task to be analyzed. The task is described by its cues and their priority for motion information given in Table E.5.

Next, the procedure determines whether the task is trainable in this simulator alternative by comparing the simulator fidelity with the task's cues and their priority for motion information. If some of the task's cues have motion as their primary (most important) source, the task is not trainable in the simulator unless its fidelity is adequate for all such cues. For example, if the task requires some type of yaw information whose primary source is motion, it would be trainable in a simulator with a platform but not in one with a g-seat or one without motion. If none of the task's cues has motion as its primary source, then the task is trainable with every simulator alternative we consider because they all provide adequate information from visual, instrument, and aural sources.

If the task is trainable in this simulator, then its suitability code from Table E.10 shows directly how it is to be tallied. But the tallying becomes more complicated if the task is not trainable in this simulator. For example, if the suitability code indicates that a task is *in principle* trainable in both a simulator and an aircraft but if *in practice* it is not trainable in a particular simulator alternative, then the task would be tallied as trainable in the aircraft only. Likewise, if the suitability code indicates that a task is *in principle* trainable

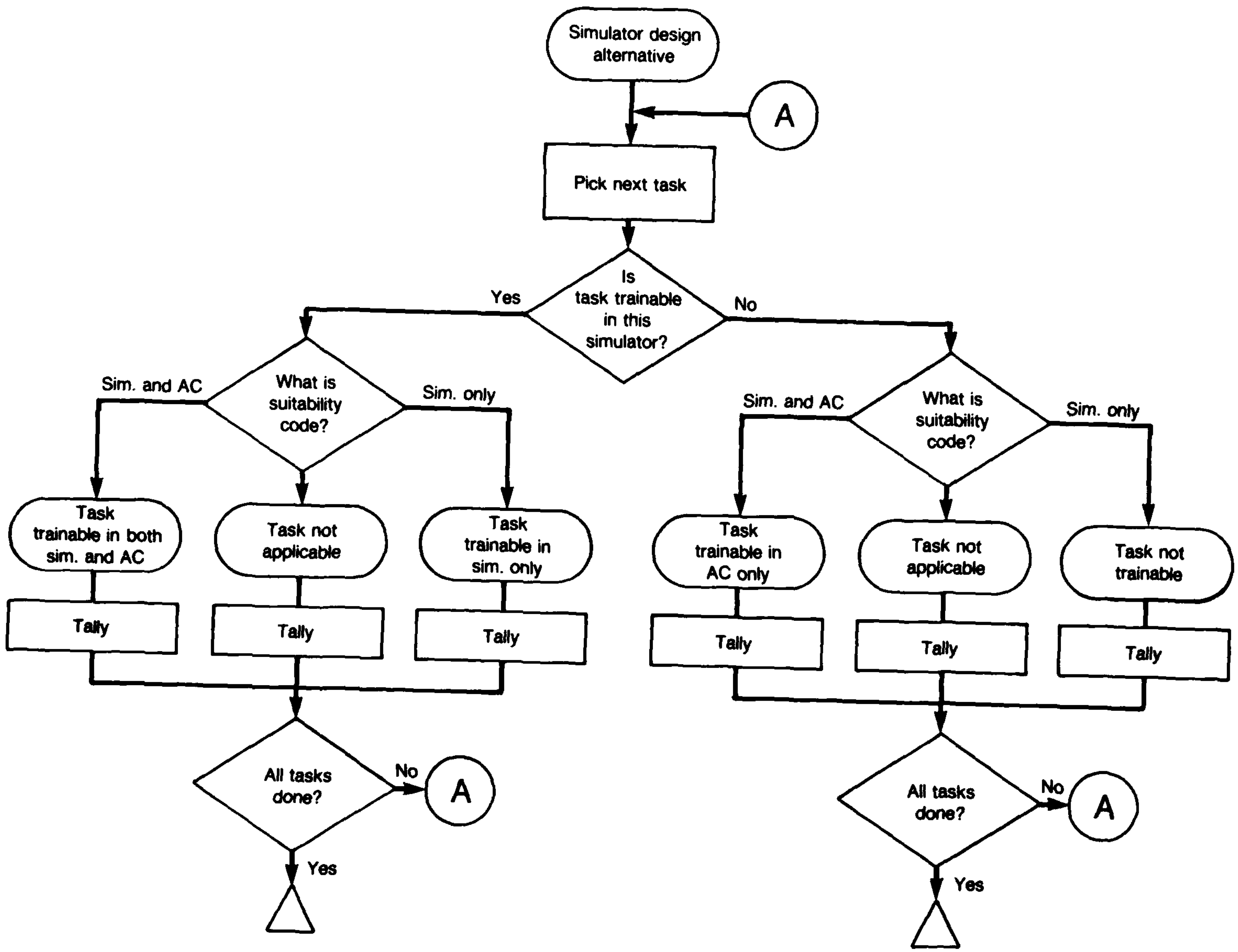

Fig. E.3 -- Procedure for counting trainable tasks

Table E.17

ADEQUACY OF MOTION INFORMATION FROM
ALTERNATIVE MOTION-CUEING DEVICES

(A = Adequate)

Type of Motion Information	Six-dof Platform	"Pessimistic" G-Seat	"Reference" G-Seat	"Incredible" G-Seat
Constant g-loading	A	A	A	A
Constant deck angle	A	A	A	A
Change in pitch	A	A	A	A
Buffet in pitch	A	A	A	A
Change in speed (accel/decel)	A	A	A	A
Change in roll	A		A	A
Buffet roll	A		A	A
Uncoordinated flight (yaw out of trim)	A			A
Change in yaw	A			A
Buffet yaw	A			A

NOTE: Appendix D provides the rationale for these assignments of adequacy.

in the simulator only (and for reasons of prudence or difficulty not in the aircraft) but if *in practice* it is not trainable in a particular simulator alternative because of the absence of adequate motion cues, then the task would be tallied as not trainable.

The procedure continues in this fashion until all the tasks being considered have been assessed.

Procedure for Counting Task Variations from Combat Conditions

Figure E.4 shows the procedure we developed for counting task variations from combat conditions. This procedure is the same as the preceding one except for two differences:

- Only mission tasks are used because those are the only flight situations in which combat conditions would be experienced by a crew.

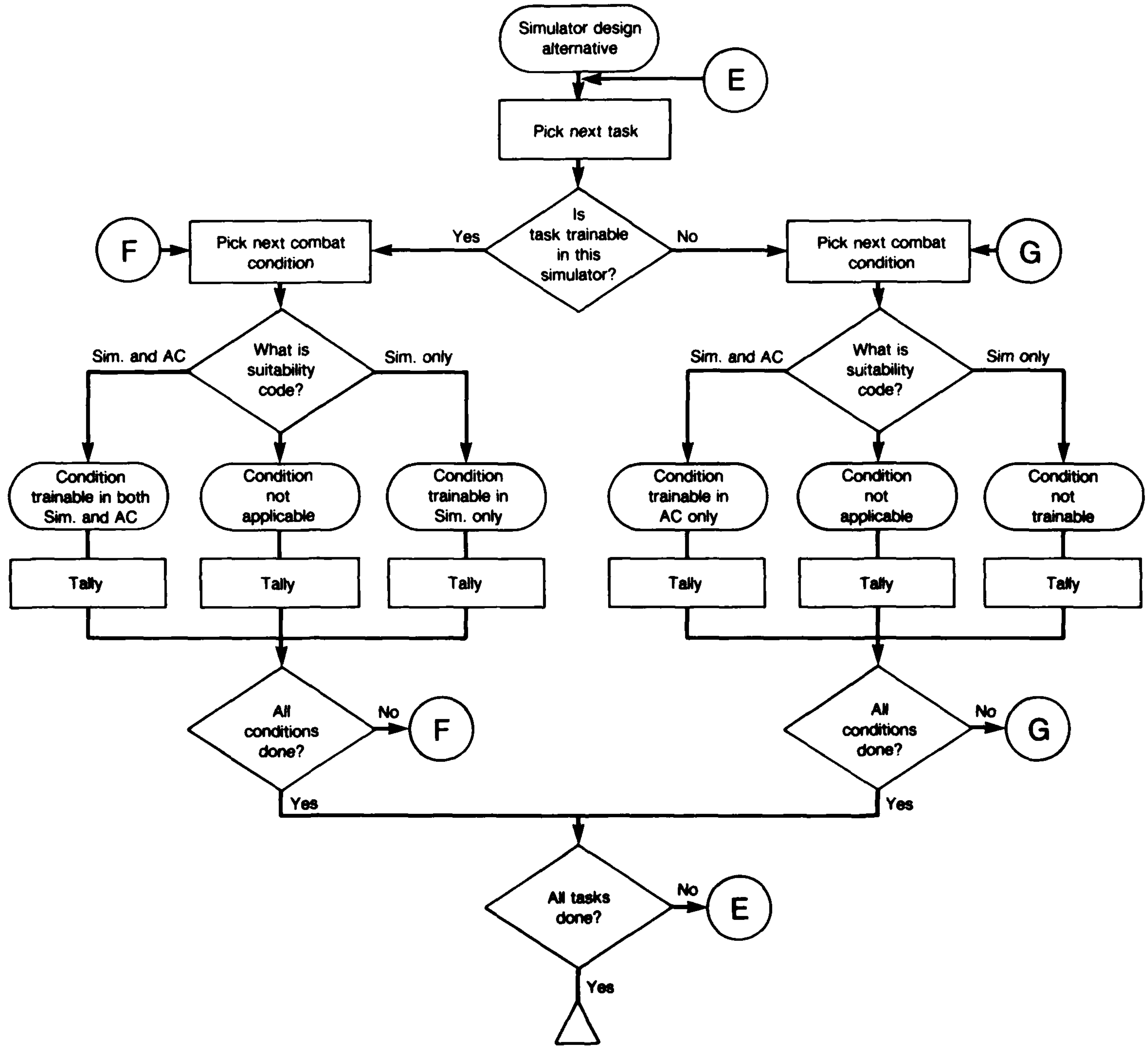

Fig. E.4 -- Procedure for counting task variations from combat conditions

- Suitability codes are those for combinations of mission tasks and combat tasks as given in Table E.16.

Procedure for Counting Task Variations from Environmental Conditions

Figure E.5 shows the procedure we developed for counting task variations from environmental conditions. This procedure differs from the preceding in four respects:

- Environmental conditions can be applied to all tasks, not just to combat missions, because they can in principle be experienced over the full spectrum of tasks.
- Suitability codes are those for combinations of tasks and environmental conditions as given in Table E.16. The aircraft, which might otherwise be suitable for training a particular task, may not be suitable under certain environmental conditions, such as thunderstorms. Thus, the suitability codes will change under such environmental conditions.
- Once the procedure determines whether a task is trainable, it picks the next environmental condition to examine, with the condition being described by the types of information that are affected by it as given in Table E.9.
- The procedure compares the condition's description with the task's cues.[19] If the condition affects at least one of these cues, then the condition is tallied as before, depending on the suitability code and whether the task is trainable. But if the condition does not affect even one of these cues, then the

[19]We consider not only cases in which motion is the primary source but also those cases in which it is a secondary source of information. In the later case, we want to determine whether the environmental condition affects motion. This helps us differentiate the capabilities of the three alternatives that can all supply the primary information equally well--whether it be from visual, aural, or instrument sources.

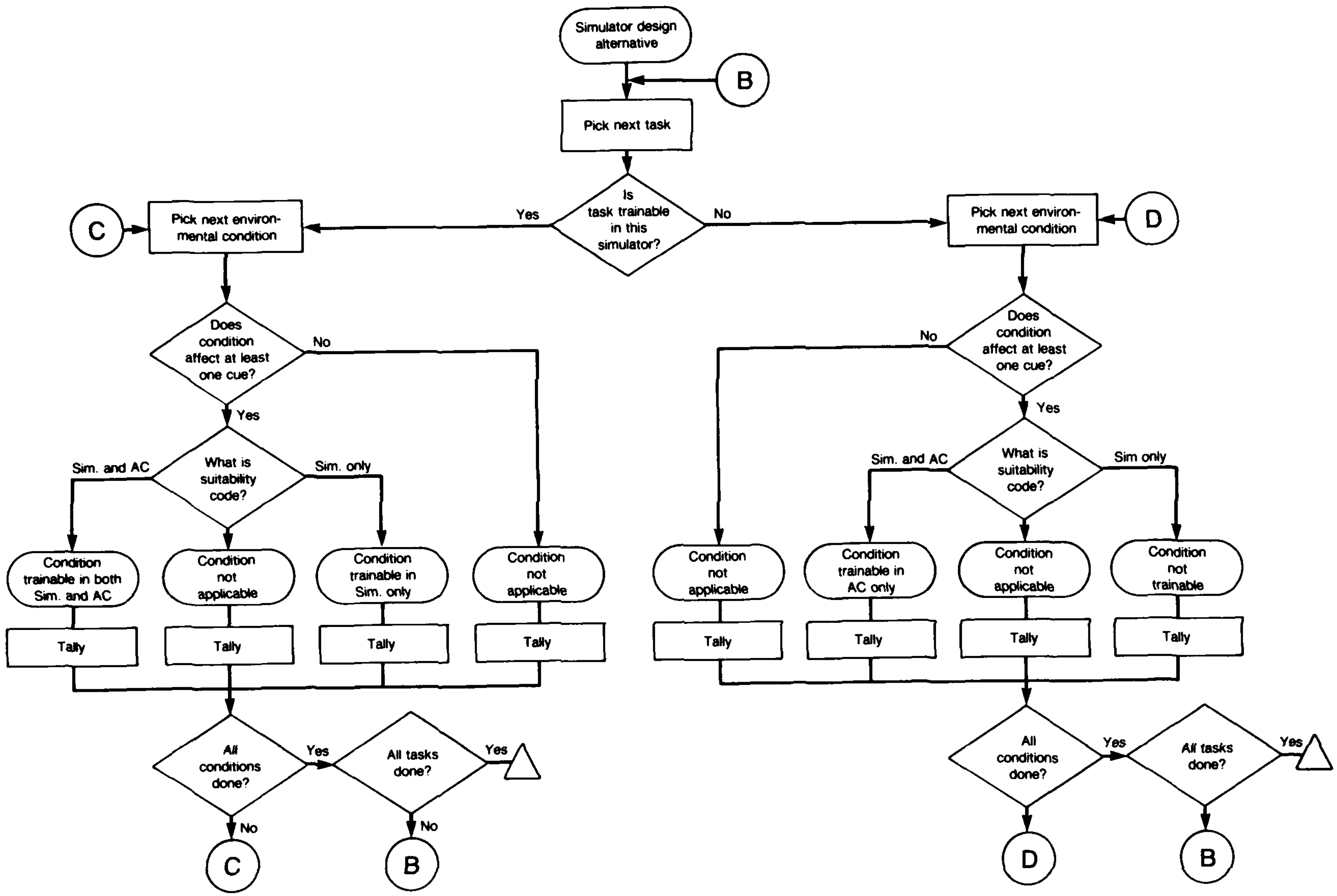

Fig. E.5 -- Procedure for counting task variations from environmental conditions

condition is simply tallied as "not applicable"; it would not have affected cues in the aircraft.[20]

Procedure for Counting Task Variations from Combination of Combat and Environmental Conditions

Although we did not use this procedure in our analysis, we briefly describe it here because others may find it a useful method to assess, for example, a simulator's training capability for special missions, such as an assault landing for a particular operating site in a variety of crosswinds.

This procedure is an extension of the procedure described in Fig. E.5. After determining how to tally a particular environmental condition for a particular task, we compare the suitability code for the combat condition with the tally decision for the environmental condition to determine how to tally their combination. If either is "not applicable," then that is how we tally their combination. If both are trainable in both the simulator and the aircraft, then we tally the combination that way. If one is "simulator only" and the other is either "simulator only" or "both simulator and aircraft," we tally it as "simulator only." If one is "aircraft only" while the other is either "aircraft only" or "both simulator and aircraft," we tally it as "aircraft only." And if one is "simulator only" and the other is "aircraft only," we tally the combination as "not applicable."

EXTENDING THE METHODOLOGY TO OTHER APPLICATIONS

We have used our methodology to compare simulator concepts that are different in their force (motion) cues but identical in their aural, instrument, and visual cues. Our methodology can, however, also be applied to compare alternatives that differ in visual cues or in visual

[20]We compare the condition's description with the cues from the aircraft rather than with the cues that the simulator can adequately provide (which may be fewer) for the following reasons. If a task is *trainable in the simulator*, then the simulator will adequately provide the same cues as the aircraft; thus we can use the cues from the aircraft. If a task is *not trainable in the simulator*, then the task will be trained in the aircraft, if at all; thus we again can use the cues from the aircraft.

and force (motion) cues. For example, our methodology could compare narrow-field versus wide-field visual systems or visual systems that differ in scene detail (number of surfaces) and quality (brightness, resolution, texture, etc.).

However, using our methodology for such purposes would require modifying and extending the methodology of the DOT/FAA Report which we have employed to produce data on cues, sources, and priorities. The following are some modifications and extensions that may be needed:[21]

1. The list of tasks considered in the visual cue analysis (DOT/FAA Report, Sects. V and VI and App. D) should explicitly include the malfunctions and additional maneuvers, rather than treating them as "overlays" on the basic tasks, and it should also include the mission tasks.
2. In the tables showing the priority for different types of motion information (e.g., DOT/FAA Report, Table E-1), the primary source (priority = 1) should be identified as visual, force (motion), aural, or instrument for each cue. When motion is shown as the priority 2 source, it is currently unclear which source is priority 1.
3. In Tables VI-1 and VI-2 of the DOT/FAA Report, which summarize the priorities for visual information and the requirements for their sources by flight segment (taxiing, takeoff, approach, landing), some additional types of segments may be needed to adequately reflect the malfunction and mission tasks, for these differ considerably from the basic tasks. Indeed, it is conceivable that one or both of these tables would be needed by task rather than by segment.

Some modifications of our assessment methodology would also be needed. Although we cannot be definitive without knowing the precise modifications to the DOT/FAA methodology, we believe they would probably include the following:

[21]Since we have neither studied the problem of modifying and extending the methodology nor performed comparisons of different visual systems, we must stress that the following descriptions should be viewed as indicative rather than definitive.

1. Determining whether a task is trainable by examining not only the types of motion information, as before, but also the types of visual information.
2. For visual information whose priorities are defined somewhat differently than those for motion information, determining the priority that should be used in the criteria for defining a trainable task.
3. Establishing not only criteria for determining whether a simulator adequately provides different types of visual information but also the approach to determining simulator visual fidelity.

This final modification is tantamount to developing a new version of App. ST of the DOT/FAA Report for visual information. Table VI-2 in the DOT/FAA Report summarizes requirements for sources of visual information (e.g., parallax, relative motion, terrain patterns). It might provide a good starting point for this activity if it were combined with a clear linkage from the sources to the types of information (e.g., vertical movement, rate of turn, pitch angle).

Appendix F

BENEFITS OF SIMULATOR MOTION FOR TRAINING CAPABILITY

by

B. F. Goeller and L. M. Jamison

We applied the simulator training capability assessment methodology described in Appendix E to three alternative simulator concepts. All three provide the same faithful representation of all appropriate aural cues, instrument cues, and flight control responses. In addition, all provide the same visual cues, namely a wide field-of-view visual system, including peripheral cues, that treats day/night/dusk. However, they differ in their motion cues: the first includes no motion, the second a hydraulic/pneumatic g-seat,[1] and the third a six-dof synergistic motion platform.

NUMBER OF TRAINABLE TASKS

We applied the methodology to all 76 tasks to determine the number of trainable tasks for the three alternatives (see Table F.1).

With the motion platform alternative, all 76 tasks are trainable. But with the g-seat alternative, 11 (14 percent) are not trainable--that is, they cannot be trained in the aircraft for reasons of prudence or difficulty and the simulator does not provide adequate cues. The no-motion alternative is even more limited: 17 of these tasks (22 percent) are not trainable.

With the no-motion alternative, 39 of the tasks (51 percent) can only be trained in the aircraft. With the g-seat, 30 of the tasks (39 percent) can only be trained in the aircraft. With the motion platform alternative, none must be trained in the aircraft.

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[1]This is the "reference g-seat," having the capabilities defined in Appendix D.

Table F.1

NUMBER OF TRAINABLE TASKS

	Simulator Alternative		
Tasks	No Motion	G-Seat	Motion Platform
Trainable in			
Both simulator and aircraft	11	20	50
Simulator only	9	15	26
Aircraft only	39	30	0
	59	65	76
Not trainable	17	11	0

The platform alternative can train all 76 tasks. The no-motion alternatives can only train 20 (26 percent) while the g-seat alternative can only train 35 (46 percent).

To illustrate how different tasks were counted and the reasons why, Table F.2 shows the trainability of selected tasks for the different alternatives, along with the reason for any change in trainability. For example, the reject-takeoff task is trainable in both the simulator and the aircraft for all three alternatives because motion is not the primary information source for any required cue. In contrast, although LAPES is trainable in both the motion platform simulator and the aircraft, it becomes trainable only in the aircraft under the other alternatives because they lack the motion information that is the primary source for the required lateral cues (yaw). Finally, the asymmetric/split flaps malfunction is not trainable in the aircraft for reasons of prudence and difficulty. Although it is trainable with the motion platform and g-seat alternatives, it is not trainable at all with the no-motion alternative because that alternative cannot provide the motion information that is the primary source of the required pitch cue.

Table F.2

TRAINABILITY OF SELECTED TASKS (BY ALTERNATIVE)

Tasks	Suitaability Code	Simulator Alternative: Platform	G-Seat	No Motion	Reason for Changes
Basic tasks					
Reject takeoff	+	B	B	B	NM
Emergency descent	P	S	N	N	LM
Circling-to-land maneuver	+	B	A	A	LM
Additional maneuvers					
Steep turns	+	B	A	A	LM
Flap/slat extension/retraction	+	B	B	A	PM
DLC spoiler extension/retraction	+	B	A	A	LM
STOL landing	+	B	A	A	LM
Malfunctions					
One engine fails in flight	+	B	A	A	LM
Asymmetric/split trailing edge (TE) flaps	P/D	S	S	N	PM
Asymmetric leading edge (LE) devices	P/D	S	N	N	LM
Antiskid fails	P	S	S	S	NM
No reverse (one engine) on landing	+	B	A	A	LM
One engine fails on rotation	P	S	N	N	LM
Mission air drop extraction failure	P/D	S	N	N	LM
Mission tasks					
LAPES	+	B	A	A	LM
In-flight refueling	+	B	A	A	LM
Assault landing	+	B	A	A	LM

NOTES: B = trainable in both simulator and aircraft
S = trainable in simulator only
A = trainable in aircraft only
N = not trainable
NM = motion not primary source for any required cue
LM = motion is primary source for lateral cues
PM = motion is primary source for change in pitch

SUITABILITY CODES:
P = not prudent to train in aircraft
D = too difficult to train in aircraft
X = not applicable
\+ = trainable in both simulator and aircraft

NUMBER OF TRAINABLE TASK VARIATIONS FROM COMBAT CONDITIONS

We applied the procedure of Fig. E.4 to the nine combat missions and five types of combat conditions to determine, for all three alternatives, the number of task variations from combat conditions that were trainable. Of the 45 possible task variations, we found that only 34 could realistically be trained. Table F.3 shows the results of the analysis for these variations.

With the motion platform alternative, all 34 sensible variations are trainable. But with the no-motion alternative 17 of these are not trainable, and with the g-seat alternative 10 of these are not trainable.

With the no-motion and g-seat alternatives, 14 of these tasks (41 percent) can only be trained in the aircraft. With the motion platform alternative, none must be trained in the aircraft.

The motion platform alternative can train all 34 sensible variations. The no-motion and g-seat alternative can train only three, which is less than 10 percent.

To illustrate how different variations were counted and the reasons why, Table F.4 shows the trainability of variations of selected tasks for the different alternatives, along with the reason for any change in

Table F.3

NUMBER OF TRAINABLE TASK VARIATIONS UNDER COMBAT CONDITIONS
FOR NINE MISSION TASKS

	Simulator Alternative		
Task Variations	No Motion	G-Seat	Motion Platform
Trainable in			
Both simulator and aircraft	3	9	17
Simulator only	0	7	17
Aircraft only	14	8	0
	17	24	34
Not trainable	17	10	0

Table F.4

TRAINABLE VARIATIONS OF SELECTED TASKS: VARIATIONS FROM COMBAT CONDITIONS

Task	Suitability Code	Combat Condition	Suitability Code for Combination of Task and Condition	Simulator Alternative			Reason for Changes
				Platform	G-Seat	No Motion	
LAPES	+	Load	P	S	N	N	LM
		Enemy activity	P/D	S	N	N	LM
		Operating site	+	B	A	A	LM
In-flight refueling	+	Load	+	B	A	A	LM
		Enemy activity	X				
		Operating site	X				
Assault landing	+	Load	P	S	N	N	LM
		Enemy activity	P/D	S	N	N	LM
		Operating site	+	B	A	A	LM
Back taxiing	+	Load	+	B	B	B	NM
		Enemy activity	X				
		Operating site	+	B	B	B	NM

NOTES:
B = trainable in both simulator and aircraft
S = trainable in simulator only
A = trainable in aircraft only
N = not trainable
NM = motion not primary source for any required cue
LM = motion is primary source for lateral cues

SUITABILITY CODES:
P = not prudent to train in aircraft
D = too difficult to train in aircraft
X = not applicable
\+ = trainable in both simulator and aircraft

trainability. For example, operating site is a trainable variation of the back-taxiing task in both the simulator and the aircraft for all three alternatives because motion is not the primary information source for any required cue. In contrast, although operating site is a trainable variation on the assault landing task in both the platform simulator and the aircraft, it becomes trainable only in the aircraft under the other alternatives because they lack the required lateral cues (yaw) for which motion is the primary source.

NUMBER OF TRAINABLE TASK VARIATIONS FROM ENVIRONMENTAL CONDITIONS

We applied the procedure of Fig. E.5 to the nine combat missions and 11 types of combat conditions to determine, for all three alternatives, the number of task variations from environmental conditions that were trainable. Of the 99 possible task variations, we found that only 53 could realistically be trained. Table F.5 shows the results of the analysis for these variations.

Table F.5

NUMBER OF TRAINABLE TASK VARIATIONS UNDER ENVIRONMENTAL CONDITIONS FOR NINE MISSION TASKS

	Simulator Alternative		
Task Variations	No Motion	G-Seat	Motion Platform
Trainable in			
Both simulator and aircraft	0	0	3
Simulator only	6	6	50
Aircraft only	2	3	0
	8	9	53
Not trainable	45	44	0

With the motion platform alternative, all 53 sensible variations are trainable. But with the no-motion and g-seat alternatives, 85 and 83 percent of the task variations are respectively not trainable.

With the no-motion alternative, two of the tasks can only be trained in the aircraft. Similarly, with the g-seat alternative, three tasks can only be trained in the aircraft. With the motion platform alternative, none must be trained in the aircraft.

The motion platform alternative can train all 53 sensible variations. The no-motion and the g-seat alternatives can train only six (11 percent).

To provide some illustrations, Table F.6 shows the trainability of variations of selected tasks for the different alternatives, along with the reason for any change in trainability. As an example, consider the environmental condition of airframe icing, which is not trainable in the aircraft for reasons of prudence and difficulty. Airframe icing is a trainable variation of the LAPES task in the platform alternative, but is not trainable under the other alternatives because they cannot provide the motion that is the primary information source of the required lateral cues (uncoordinated flight and yaw). As another example, the ground effect is a trainable variation of the LAPES task in the aircraft and the platform alternative, but it becomes trainable in only the aircraft under the other alternatives because they lack that motion information.

SENSITIVITY ANALYSIS

We recomputed the number of trainable tasks and the task variations in the preceding sections for the "pessimistic g-seat" defined in Appendix D. The results were generally the same or slightly smaller (i.e., fewer tasks trainable in the simulator) than those for the "reference g-seat." The lack of lateral cues, which appears innate to the g-seat, dominates the results.

Table F.6

TRAINABLE VARIATIONS OF SELECTED TASKS:
VARIATIONS FROM ENVIRONMENTAL CONDITIONS

Task	Suita-bility Code	Environmental Condition	Suitability Code for Combination of Task and Condition	Simulator Alternative			Reason for Changes
				Platform	G-Seat	No Motion	
LAPES	+	Crosswind	D	S	N	N	LM
		Airframe icing	P/D	S	S	N	DM
		Turbulence	D	S	N	N	LM
		Ground effect	+	B	B	A	PM
In-flight refueling	+	Crosswind	X	S	N	N	LM
		Airframe icing	P/D	S	N	N	LM
		Turbulence	D				
Assault landing	+	Crosswind	D	S	N	N	LM
		Airframe icing	P/D	S	N	N	LM
		Turbulence	D	S	N	N	LM

NOTES: B = trainable in both simulator and aircraft
S = trainable in simulator only
A = trainable in aircraft only
N = not trainable
NM = motion is not primary source for any required cue
LM = motion is primary source for lateral cues
PM = motion is primary source for change in pitch
DM = motion is primary source for constant deck angle
SM = motion is primary source for change in speed

SUITABILITY CODES:
P = not prudent to train in aircraft
D = too difficult to train in aircraft
X = not applicable
\+ = trainable in both simulator and aircraft

Appendix G

POSSIBLE BENEFITS OF SIMULATOR MOTION FOR SAFETY

by

T. F. Kirkwood

One goal of this study was to identify possible safety benefits from having a simulator that could provide motion cues experienced in the aircraft during accident situations. To perform this task, we reviewed Air Force mishap[1] data to identify those mishaps where motion cues were probably critical. Our data base, derived from information supplied by the Air Force Inspection and Safety Center, Norton Air Force Base, consisted of 169 mishaps (of which 29 involved fatalities) for non-centerline-thrust Air Force aircraft from January 1975 to January 1985.

We examined the description of these mishaps and, using our judgment, we classified them according to three categories:

- Motion cues possibly critical
- Motion cues available but other cues adequate
- Motion cues of no value.

There were mishaps in which several cues were available, but motion might have provided the first indication of trouble (outboard engine failure, for example). In these cases, if the failure occurred at high altitude and it was clear that other cues would have provided the same information within a few seconds, we did not count the motion cue as being "critical." If the same situation occurred at low altitude, where time was important, we counted the motion cue as "critical."

[1]The Air Force defines a mishap as any accident involving a fatality or a cost on the order of $100,000.

There are a large number of mishaps in which motion cues are either not present, are of no value, or would not be simulated in the trainer. These include mishaps due to pilot error (landing short of the runway, hitting a mountain while avoiding weather, etc.), component failure (wing collapse, landing gear failures on landing or takeoff), and happenstance (lightning strike, mid-air collision).

Table G.1 shows the breakdown of mishaps into three groups. It indicates that two-thirds of the mishaps involved situations in which motion would be of no value. Slightly over half of the remaining mishaps could have been handled without motion (and so could have been trained for on a simulator without motion), but the remaining 15 percent of mishaps involved situations in which motion may have provided a critical cue. Presumably, training in a simulator with motion would be beneficial in these cases, although training without motion might be adequate if followed by brief training or experience in the actual airplane.

Three-quarters of the 56 mishaps in which motion cues were either critical or available involved engine failure. Further, one-third of these engine failures were due to birdstrikes. If future engines became

Table G.1

OCCURRENCE OF MOTION CUES IN AIR FORCE MISHAPS
(1975-1985)

Mishap Category	Number of Mishaps	Percent
Motion cues possibly critical	26	15
Motion cues available but other cues adequate	30	18
Motion cues of no value		
Pilot error	35	21
Component failure	59	35
Happenstance	19	11
Total	169	100

more reliable, and if more attention is given to designs that prevent birdstrikes, mishaps in which motion can be useful may be significantly reduced.

While we found that about 15 percent of the mishaps (26 mishaps) involved situations in which motion cues might have been critical, about 28 percent of the *fatal* mishaps involved critical motion cues. This apparent increase in importance of motion cues in fatal mishaps may or may not be statistically significant. (There were only eight fatal mishaps in which motion cues may have been critical.) On the other hand, motion cues are of greatest value in situations in which time is critical and it may indeed be true that motion cues are particularly important in life-threatening situations.

Our results may thus furnish an upper bound on the effect of simulator motion on mishap rate. If we assume that pilots trained without motion in the simulator *never* learn to use motion cues in the airplane, we might expect them to be less able to cope with 15 percent of the mishaps. (It is more likely that the opposite is true: Pilots trained without motion cues will quickly learn to use them when they become available in the aircraft without any additional training. Obviously, if this were completely true we would not expect training without motion to have any effect on mishap rate.)

We examined all the mishaps in which motion cues were available to find the nature of the initial motion cue in each. (We assume that furnishing the initial cue promptly is the most important function of motion.) Table G.2 shows the breakdown of the types of failure and the initial motion cue involved in the failure.

The large number of mishaps involving engine failure make it appear that yaw about the aircraft center of gravity (producing a corresponding lateral acceleration cue in the cockpit) is the most important dof to simulate so far as Air Force mishaps are concerned. Other mishap situations that might be simulated (fin stall and wing stall) require cues in pitch (producing a vertical acceleration in the cockpit) and stall warning (either buffet or a stick-shaker) in addition to yaw. Simulation of more routine flight situations which were not involved in mishaps might require not only these, but other motion cues. If these

Table G.2

INITIAL MOTION CUES INVOLVED IN AIR FORCE MISHAPS

Types of failure	Number of mishaps	Initial cue*
Engine out	42	yaw
Landing gear collapse**	3	yaw, heave
Fin stall	1	yaw, pitch
Autopilot	2	--
Boom separation**	1	--
Wing stall	2	pitch, buffet or stick-shaker
Flap failure (asymmetric)	1	roll
Engine reversed on landing	1	yaw
Birdstrike on airframe**	2	--
Stabilizer trim	1	pitch
Total	56	

*Referenced to the aircraft center of gravity.
**Situations that probably could not, or normally would not, be simulated.

requirements are met by the use of platform motion, the simulation of mishaps probably does not drive the design of the motion system.

Appendix H

BENEFITS OF SIMULATOR MOTION IN AVOIDING SIMULATOR SICKNESS

by
M. G. Chaloupka

Simulator sickness is a term used to describe the diverse signs and symptoms that have been experienced by pilots during or after a training session in a flight simulator. Symptoms include nausea, dizziness, spinning sensations, visual flashbacks, motor dyskinesia, confusion, and drowsiness (Frank et al., 1983).

Simulator sickness is a special case or subset of motion sickness. Motion sickness is a general term for a constellation of symptoms and signs, generally adverse, due to exposure to abrupt, periodic, or unnatural accelerations. Much remains to be known about simulator sickness, but much of what is known may be found in the report of the discussions of a workshop on simulator sickness sponsored by the National Academy of Sciences (McCauley, ed., 1984).[1]

Simulator sickness potentially poses four operational problems:

1. *Compromised Training*. Symptoms experienced in the simulator may compromise training by distracting the pilot. Simulators may teach pilots to avoid simulator sickness by not looking out the window, by reducing head movements, by avoiding aggressive maneuvers, and the like. While such actions may improve a pilot's performance in a simulator, they may also hamper his performance in the airplane.
2. *Decreased User Motivation*. Because of unpleasant symptoms and after-effects, simulator users may be reluctant to return for subsequent training sessions. They also may have reduced confidence in the training they receive from the simulator.

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[1]This appendix relies extensively on the contents of this report.

3. *Ground Safety.* After-effects, such as disequilibrium, could be potentially hazardous for users when exiting the simulator or driving home.
4. *Flight Safety.* No direct evidence exists for a relationship between simulator sickness after-effects and accident probability. However, from the scientific literature on perceptual adaptation, one could predict that adaptation to a simulator's rearranged perceptual dynamics would be counterproductive in flight.

While the relation between simulator sickness and these four operational problems is currently unknown, the Navy has

- Issued cautions concerning possible adverse effects of simulator use
- In some cases restricted pilots when symptoms were noted from flying less than twelve hours following training in a simulator
- Instituted a program to identify the relative incidence of simulator sickness in its different trainers. In so doing, it will categorize symptoms using a seven-point scale ranging from no symptom to vomiting (Kennedy, et al., 1984b).[2]

In the following subsections, we survey the literature to describe a plausible theory for motion sickness, to identify its causes and incidence, and to identify those simulator and operator characteristics that may influence it.

THEORY OF MOTION SICKNESS

Ken E. Money (McCauley, ed., 1984) provides a persuasive theory concerning the reasons for motion sickness. According to Money's "poison theory," motion sickness is a response to the motion's stimulation of the vestibular system which produces an unnatural

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[2]Although the Air Force's Simulator for Air-to-Air Combat (SAAC) has been the subject of two simulator sickness studies (see Table H.1), we are unaware of similar actions by the Air Force.

activation of a normal physiological mechanism, i.e., vomiting in response to poison.

It is well known that central vestibular units can be driven by stimulating the ambient visual system (Waespe and Henn, 1977, 1978). Therefore, it is not surprising that the vestibular mechanisms can be activated by visual stimulation, as they are in simulator sickness. It is also well known that in the absence of the vestibular system, motion sickness cannot occur.

This poison theory gives credence to the sensory conflict or sensory mismatch theory of motion sickness, i.e., it is stimulation arising from peculiar motions--motions that exceed the normal dynamic limits of the vestibular system. When exposed to such motion, the vestibular system therefore sends information that is false or distorted. The brain then recognizes these inputs as false because they are in conflict with other information about motion from vision, from another part of the vestibular system, or from proprioception. The result is motion sickness. It is the false information from the vestibular system that becomes the stimulus for the brain's vomiting center.

In many situations that provoke motion sickness, no single component of the motion stimulus is either strong or nauseogenic, but in combination the sensory stimuli induce sickness. In other situations, highly nauseogenic stimuli may be rendered benign by the addition of other motion stimuli, apparently because the added stimuli remove the conflict.

Such sensory conflict is the most common explanation for motion sickness. It postulates a referencing function in which motion information from vision, the vestibular system, and proprioception may be in conflict with the expected values of these inputs, based on a neural store that reflects past experience (Kennedy and Frank, 1983).

The sensory conflict theory in its present form does not, however, satisfactorily address the coherence or predictability of the sensory mismatch.

CAUSES AND INCIDENCE OF SIMULATOR SICKNESS

Simulator sickness may be due to accelerative forces or may be caused by visual motion cues in the absence of actual movement of the subject. In all documented cases of simulator sickness, a visual display of vehicle dynamics has been involved (Dichgans and Brandt, 1973).

Simulator sickness occurs in both fixed- and motion-platform simulators. It occurs during the simulator flight, immediately afterward, and many hours later. The highest incidence (88 percent) has been reported in an air combat maneuvering (ACM) simulator during fixed platform operations, in which high visual acceleration maneuvers are common (Kellogg et al., 1980).

Experienced aviators and test pilots seem to be more susceptible to simulator sickness than inexperienced trainees. Experienced aviators have a well-established neural store representing the relationships among manual control actions, visual dynamics, and the orientation and inertial senses subserved by the vestibular/proprioceptive systems. By contrast, inexperienced aviators lack such a well-established neurophysiological expectancy for these relationships. To the extent that the simulator violates the sensory expectancies, a conflict exists (McCauley, ed., 1984).

The overall incidence of simulator sickness in flight simulators across the armed services is unknown, even though the problem was first reported nearly 30 years ago. There are suggestions, however, that the incidence is increasing. Because pilots tend not to talk about such problems, we may in fact be underestimating the problem.

Table H.1 summarizes the major studies that have been made of simulator sickness. For a more complete review, see Kennedy and Frank, 1983; Kennedy et al., 1984a; Kennedy et al., 1984b.[3]

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[3] In addition to the studies listed in Table H.1, Sinacori (1967) studied simulation techniques for vertical short takeoff and landing (VSTOL) flight. Using only one test pilot he reported: "Pilot vertigo was induced as the time duration of a particular flight increased. . . . The pilot felt he could do better with cockpit motion cues. . . Pilot vertigo may be caused by the conflict between the sometimes 'fair' visual cues acquired during attempted hover and the highly trained kinesthetic sensations which are expected but not felt because the

Table H.1

MAJOR STUDIES OF SIMULATOR SICKNESS

Report	Device	Incidence (Percent)	Base	Visual Type	Field of View (H x V)
Havron and Butler (1957)	2-FH-2	77	Fixed	PS	260 x 75
Miller and Goodson (1958, 1960)	2-FH-2	60(I) 12(S)	Fixed	PS	260 x 75
Hartman and Hatsell (1976)	SAAC	52	Moving	CIG	296 x 180
Kellogg, Castore, and Coward (1980)	SAAC	88	Fixed[a]	CIG	296 x 180
Money (1980)	CF140 FDS	43	Moving	T/N/CIG	48 x 36(?)[b]
McGuinness, Bouwman, and Forbes (1981)	2E6	27	Fixed	T/PS CAM MOD	360 x 150
Frank (1981)	2F112	10	Fixed	T/PS CAM MOD	360 x 150
Frank (1981)	2F110	48	Moving	T/N/CIG	120 x 36
Crosby and Kennedy (1982)	2F87	50	Moving[c]	T/N/CIG	48 x 36[b]
Frank and Crosby (1982)	2F117	---	Moving	CIG	175 x 50

SOURCE: Kennedy et al. (1983).
NOTES: PS = point source; T = twilight; N = night; CIG = computer image generation; CAM MOD = target camera model; I = instructors; S = students.

[a]Motion not used in study.

[b]One window.

[c]Motion or lack of motion had no effect.

Havron and Butler (1957), the first published report on simulator sickness, found a substantial incidence of symptoms among users of the Navy's 2-FH-2 Hover Trainer.

Miller and Goodson (1960) found that "the more experienced instructors seemed to be the most susceptible to unpleasant sensations." Moreover, "the more violent maneuvers were found to produce a greater degree of motion sickness. Instructors have reported that they are more prone to become sick when sitting as a passenger . . . than when actually flying the simulator." Miller and Goodson also reported the occurrence of delayed effects in an instructor pilot who became "so badly disoriented in the simulator that he was later forced to stop his car, get out, and walk around in order to regain his bearings enough to continue driving."

Hartman and Hatsell (1976) found incidence of simulator sickness in moving platforms with computer image generation and wide field-of-vision visuals.

Kellogg et al. (1980) studied simulator sickness during fixed-platform operations in the Air Force SAAC. Of the 48 pilots who were undergoing intense exposure, more than 87 percent reported some symptoms of simulator sickness, primarily nausea. Symptoms were most prevalent in the first few days. Pilots reported visual flashbacks, sometimes eight to ten hours after exposure.

Money (1980) investigated reports of simulator sickness in the Aurora CP-140 (the Canadian version of the U.S. Navy P-3). He found that 43 percent of the pilots reported symptoms, ranging from slight discomfort to mild nausea. The symptoms were usually experienced only in the first one or two simulator exercises. Subsequent exercises were symptom-free, presumably due to habituation.

McGuiness et al. (1981) investigated the incidence of simulator sickness among 66 aircrewmen in the Navy's F-4/F-14 ACM simulator and reported an overall incidence of 27 percent. However, the more experienced aircrews, those with more than 1500 lifetime flight hours, had an incidence of 50 percent, while those with less than 1500 hours

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cockpit is fixed. Inadvertent pilot head motions were observed frequently."

had an incidence of 18 percent. There were no reports of visual flashbacks. Dizziness was the most frequent symptom, followed by vertigo, disorientation, "leans," and nausea.

Frank (1981) reported that approximately 10 percent of those using the Navy's F-14 simulator experienced symptoms of simulator sickness and that approximately 48 percent of those sampled in the E-2C simulator experienced symptoms. In the latter, several of the pilots commented that the visual streaming that occurred during turns-while-taxiing was particularly disconcerting.

Crosby and Kennedy (1982) found that flight engineers were having problems in the P-3C simulator. They found that the flight engineer was viewing the independent CRT/CGI displays of the pilot and copilot from 30 degrees off axis. Measures of postural equilibrium indicated significant decrements in 50 percent of the flight engineers after a normal four-hour exposure in the simulator. Occluding the flight engineer's view of the pilot's and copilot's displays eliminated the problems.

Frank and Crosby (1982) investigated the 2F117 while it was in the final stages of production. They reported some tendency for symptoms of simulator sickness and suggested that a more rigorous study be conducted after the introduction of the 2F117.

This brief review shows a constellation of effects that have been found during or after exposure to flight simulation. These effects include the classic symptoms of motion sickness and phenomena associated with perceptual adaptation. The overall incidence and severity of the problem across a broad spectrum of flight simulators, however, has not been established.

CHARACTERISTICS THAT MAY INFLUENCE MOTION SICKNESS

A large number of simulator and operator characteristics are suspected of playing a role in simulator sickness. Particularly suspect are time-lags associated with the display of both visual and motion cues brought about by hardware and software shortcomings.[4]

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[4]This subsection draws on discussions held at the National Academy of Sciences Workshop on Simulator Sickness (McCauley, ed., 1984).

Time-Lags in Displaying Visual and Motion Cues

Time-lags may occur in the visual system, the motion system, or both. Lags should be defined with reference to the temporal relationships found in the aircraft, as well as to the usual description of total time. As an example, suppose that 50 msec elapsed between a pilot's roll input with the stick and the beginning of the aircraft roll. Given the same input in the simulator, realistic estimates of lags might be 250 msec before the visual system begins to respond and 350 msec for the motion platform in older simulators.[5] There are thus several sources of error for the highly tuned neural store of the experienced pilot: a 200 msec lag in the visual, a 300 msec lag in the inertial, and a 100 msec discrepancy between the two.

Moreover, lag is just one index of the fidelity of dynamic information. The accelerative responses of the visual and inertial systems should not only begin at the proper time, but follow the rise time and the amplitude characteristics with reasonable fidelity.

Experienced pilots have learned a set of temporal and spatial patterns in the aircraft related to control stick inputs and the resultant visual, vestibular, and proprioceptive feedback of acceleration information. In the simulator, they are confronted with a new set of temporal and spatial patterns, i.e., lags, rise times, washout, etc. This discrepancy is probably the main source of simulator sickness.

Why are experienced pilots more susceptible to sickness? Perhaps only people who are very susceptible to motion sickness are likely to have a problem when they are inexperienced, but as experience is acquired, the less susceptible pilots also may be affected. This is because highly experienced pilots may not tolerate as much error between visual and motion cues.

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[5]See Table D.1 for comparisons of the response time of early motion platforms and more recent devices.

Characteristics of Visual Systems

Several types of visual systems have been used in flight simulators. Cases of simulator sickness have been documented in computer generated imagery and point-light-source visual systems, but they seem to be less frequent in model board systems.

One of the important variables for simulator sickness is the field-of-view (FOV) of the visual system. A wider FOV provides more stimulation for the ambient system, resulting in a more compelling visual display of motion. This enhanced sense of visual motion may contribute to more conflict with vestibular inputs, which are relatively impoverished in the simulator.

Scene detail may also contribute. Greater scene detail provides the human visual system with more information about spatial dynamics, presumably sharpening the perception of motion and generating greater potential conflict with the vestibular inputs.

There has been some suggestion that the detailed process of writing a visual display across the screen may be registered by the human visual system. This may create an unusual visual stimulus of simultaneous movement in different directions in adjacent locations. It is possible that these kinds of stimuli may contribute to simulator sickness.

Some simulators have visual systems with a 2:1 interlace system in which the video imagery is updated by the computer at 30 Hz but the display is updated at 60 Hz. With this type of system it is inevitable that moving targets create double images, which may create illusory movement and other problems, such as a strobing effect.

Other features of visual displays have been cited as potential contributors to the problem, e.g., poor resolution, flicker, and off-axis viewing. Much is not known of the implications of visual systems and their contribution to the incidence of simulator sickness.

Characteristics of Motion Platforms

The majority of present military flight simulators have motion platforms. Because of the displacement limitations, motion systems are driven by command signals using washout algorithms that permit high fidelity of movement response, with subsequent diminution of the motion

response even though the accelerations associated with the maneuver (and implied by the visual display) continue.

The responsiveness of a good motion platform provides vestibular and proprioceptive cues to motion for subtle aircraft maneuvers, although the motion platform can lag behind when extreme maneuvers are simulated.

Kennedy and Frank (1983) have emphasized the importance of simulator resonant frequency as a possible contributory factor to simulator sickness. It is known that symptoms are greatest at a frequency of about 0.2 Hz (Kennedy and Frank, 1983).

Characteristics of Other Cueing Devices

In addition to a motion platform, g-seats, g-suits, helmet loaders, and other devices have been used in flight simulators to provide pseudo-inertial cues to the pilot. The cueing algorithms of these devices require further development to match the motion platform for proper temporal patterns.

G-seats can have longer lag-times that must be compensated for, and they change the pilot's eye-point relative to the visual display (see Appendix D). Although these factors have not been thoroughly studied, they seem to indicate that devices other than motion platforms may cause more problems with simulator sickness because of their greater distortions of reality.

SUMMARY

We must stress that much remains unknown concerning simulator sickness. Sensory conflict is the most common explanation and supports the findings and opinions that:

- Experienced pilots are more susceptible to simulator sickness than inexperienced ones; and
- Experienced and inexperienced pilots are more susceptible to simulator sickness if simulators lack expected visual and motion cues and if simulators do not present these cues in a realistic fashion.

Hence, increased risks of simulator sickness--albeit difficult to characterize--may result from procuring a simulator that lacks a good motion system.

Appendix I

COSTS OF SIMULATOR MOTION SYSTEMS

by

A. A. Barbour and J. L. Birkler

Since no C-17 simulators have been built, we gathered cost data on a variety of Air Force, Navy, and commercial simulator systems. We collected detailed acquisition data on six simulators, with partial data on another two. Although the final analysis drew primarily from contractor-furnished data for military transport and nonwide-body-type commercial simulators, all of the data were analyzed and cross-checked to derive our cost estimates for a C-17 simulator.

In the subsections that follow, we

- Review our *approach* by describing our data collection methods and ietailing the assumptions that underlie our cost estimates.
- Report our *analytical results* regarding the acquisition, operations and support (O&S), and facilities contributions to simulator life-cycle costs (LCC) and quantify the incremental cost for each due to the inclusion of a motion platform.
- Describe *sensitivity analyses* involving the effects on costs of assumptions concerning the extent to which simulators are used and the number of simulators that are procured.

APPROACH

Data Collection Methods

The objective of this research was to quantify both the primary and secondary costs of including motion in a flight simulator system. Primary costs are costs directly attributable to the motion system, such as motion system hardware, computers/software, motion system O&S, the incremental cost of the larger training facilities that a six-dof motion

platform simulator requires, and the like. Secondary costs are costs indirectly attributable to the motion system, such as the additional cost to the visual system due to its being mounted on a moving platform, the additional costs for collecting data specific to driving the motion system, the additional operational site activation cost due to the motion platform, and the like.

The existing data base for U.S. Air Force simulators at the Simulator System Program Office (Sim SPO) proved less than satisfactory for our purposes since it did not address all the LCC components. It lacked information on the O&S and facilities costs generated by simulator motion systems, and the Work Breakdown Structure (WBS) cost elements consisted mostly of parametric estimates rather than actual historical cost data.

In the absence of adequate historical data bases, we set out to collect three kinds of cost data to support an LCC analysis:

- Acquisition
- Facilities
- O&S.

We collected acquisition cost data for prototype and production simulators using the standard WBS for Aircraft Simulators,[1] with columns added to capture the secondary costs of the g-seat and six-dof motion platform (see Table I.1). Acquisition data were collected from the U.S. Air Force, the U.S. Navy, and manufacturers of fighter, attack, patrol, strategic, military transport, and commercial transport aircraft simulators. While our final estimates of acquisition costs largely rest on data involving military and commercial transports, data involving all types of aircraft contributed to our understanding of relationships between the motion platform and software costs.

We collected facilities cost data from Headquarters, Military Airlift Command (MAC DEE) and the Army Corps of Engineers.

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[1]See *Standard Work Breakdown Structure for Aircraft Simulators*, 1980, Sect. VII.

Table I.1

STANDARD WORK BREAKDOWN STRUCTURE FOR AIRCRAFT SIMULATORS

Code Number	WBS Element		Percent of Costs Due to Six-dof Motion Base*
1	Simulator System	$________	________
1.1	Simulator	$________	________
1.1.1	Hardware Integration and Assembly	$________	________
1.1.2	Student Station Hardware	$________	________
1.1.3	Instructor/Operator Station Hardware	$________	________
1.1.4	Computational System Hardware	$________	________
1.1.4.1	Central Processing Unit	________%	________
1.1.4.2	Memory	________%	________
1.1.5	Visual System Hardware	$________	________
1.1.5.1	Image Generation Device	________%	________
1.1.5.2	Display System	________%	________
1.1.5.3	Structure	________%	________
1.1.5.4	Maintenance/Operator Station	________%	________
1.1.5.5	Integration and Assembly	________%	________

*Added by Rand for this study.

Code Number	WBS Element		Percent of Costs Due to Six-dof Motion Base
1.1.6	Motion System Hardware	$______	______
1.1.6.1	Structure/Base	______%	______
1.1.6.2	Hydraulic System	______%	______
1.1.6.3	Motion Platform Assembly	______%	______
1.1.6.4	Control System	______%	______
1.1.6.5	Cables	______%	______
1.1.6.6	Other Specific Hardware Elements	______%	______
1.1.6.7	Integration and Assembly	______%	______
1.1.7	G-Seat System Hardware	$______	______
1.1.8	Other Specific Hardware Elements	$______	______
1.1.9	Computer Programs/ Computer Data Integration	$______	______
1.1.10	Student Station Computer Programs/ Computer Data	$______	______
1.1.11	Instructor/Operator Computer Programs/ Computer Data	$______	______
1.1.12	Computational System Computer Programs/ Computer Data	$______	______
1.1.13	Visual System Computer Programs/Computer Data	$______	______
1.1.14	Motion System Computer Programs/Computer Data	$______	______

Code Number	WBS Element		Percent of Costs Due to Six-dof Motion Base
1.1.15	G-Seat System Computer Programs/Computer Data	$______	______
1.1.16	Other Specific Computer Programs/Computer Data	$______	______
1.1.17	Hardware/Computer Programs/Computer Data Integration	$______	______
1.2	Training	$______	______
1.4	Peculiar Support Equipment	$______	______
1.5	System Test and Evaluation	$______	______
1.6	System/Project Management	$______	______
1.7	Data	$______	______
1.7.1	Technical Publications	______%	______
1.7.2	Engineering Data	______%	______
1.7.3	Management Data	______%	______
1.7.4	Data Depository	______%	______
1.7.5	Support Data	______%	______
1.8	Operational/Site Activation	$______	______
1.9	Common Support Equipment	$______	______
1.10	Industrial Facilities	$______	______
1.11	Initial Spares and Initial Repair Parts	$______	______

We collected O&S cost data from MAC personnel reports, Air Logistics Centers, MAC Comptroller estimates, and Air Force cost factors.

All costs include burden and fee. The costs are expressed in FY85 dollars and, for the motion platform and g-seats, represent only the incremental out-of-pocket costs of adding this capability.

Assumptions

Our cost estimates reflect the following assumptions:

- Eight flight simulators, including one prototype, will be used.[2] They will replace the eight C-141 simulators presently in use on MAC bases.
- The motion platform option will provide state-of-the-art hydrostatic six-dof motion (roll, pitch, and yaw with vertical, lateral, and longitudinal translations) for each simulator. The motion platforms will be off-the-shelf systems with the following characteristics:
    - -- Six hydrostatic actuator assemblies (two-meter stroke)
    - -- Flying platform
    - -- Three-corner base
    - -- All hydraulic plumbing
    - -- Hydraulic power supply
    - -- Motion servo and safety interlock cabinet
    - -- All cables and wiring
    - -- Maintenance manuals
    - -- Motion system acceptance test procedure
    - -- FORTRAN listing of motion system drive equations
    - -- Installation at customer site
    - -- Motion system stand-alone acceptance test (three-day standard test)
- The g-seat option will provide two state-of-the-art hydraulic/pneumatic g-seats for each simulator, one for the pilot and one for the copilot. The g-seats will have the following characteristics:
    - -- Eight pneumatic bladders
    - -- Six hydraulic actuators

---

[2]We examine later in this section the sensitivity of costs to changes in the assumed number of flight simulators.

-- Seat structure
-- Lap belt
-- Air compressor
-- Hydraulic power supply
-- Maintenance control panel
-- All cables and wiring
-- Maintenance manuals
-- G-seat acceptance test procedure
-- Installation at customer site
-- G-seat stand-alone acceptance test (three-day standard test)

- The visual system will be of mid-quality with the following characteristics:

  -- Computer generated imagery (CGI)
  -- Full-daylight/full-color facsimile capability
  -- Five cathode ray tube (CRT) screens/four channels to provide a wide field of view

  The direct cost of the visual system is more than nine times greater than the cost of the motion platform and more than 14 times greater than a g-seat.[3] A higher-quality tactical visual system could cost more than twice as much as we assume here.

- The avionics will have a C-130 type configuration. It will include a simple Digital Radar Landmass navigation aid, but not sophisticated components such as penetration aids, advanced ECM equipment, low-light-level TV, forward-looking IR, and the like.

- The facilities will include the following:

  -- Five new simulator buildings
  -- Use of existing Altus facilities for the three training center simulators

- Simulators will be operated and maintained by Air Force personnel. The Air Force is now phasing in contractor maintenance for all its simulators; however, data on contractor maintenance are limited. Without exception, Air Force and contractor maintenance personnel felt this assumption represented a worst-case (highest maintenance cost) scenario for the motion system.

[3]To protect privileged information provided by our sources, we do not divulge the full details of the cost data used in this appendix.

- The Air Force will continue its current policy of using simulators 16 hours per day, five days a week.[4]

ANALYTICAL RESULTS

Using the data and the approach described in the previous subsection, we estimated the

- Acquisition costs
- Facilities costs
- O&S costs

for eight military transport type aircraft simulators. Three configurations were estimated: the no-motion alternative, the g-seat alternative, and the six-dof motion platform alternative. Costs are displayed as totals as well as average annual costs for a 25-year life cycle.

Acquisition Costs

The simulator system estimated here is composed of one transport type cockpit with all the instruments and controls. Acquisition costs consist of two components:

- One prototype
- Seven identical production units.[5]

Costs of Prototype. The prototype unit is the Full Scale Development (FSD) article that, after development has been completed, serves as one of eight training systems. Table I.2 shows the prototype costs for the no-motion alternative, the g-seat alternative, and the six-dof motion platform alternative.

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[4]We examine later in this section the sensitivity of costs to changes in the assumed number of operating hours.

[5]Because of the small numbers of simulators produced, usually no two are identical. Each unit is slightly modified/customized to the operational site.

Table I.2

PROTOTYPE COSTS

Alternative	Millions of FY85 Dollars
No motion	28.12
G-seat	28.55
Motion platform	28.90

Figures I.1, I.2, and I.3 display the distribution of costs for all three prototype configurations. Table I.3 lists the WBS elements included in each cost category.

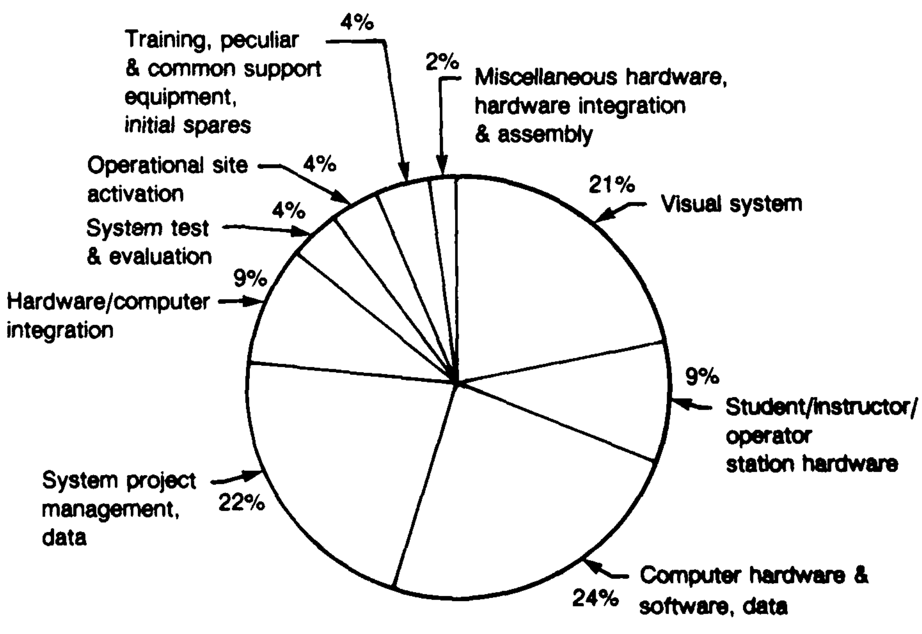

Fig. I.1 -- Cost distribution for prototype: No-motion alternative

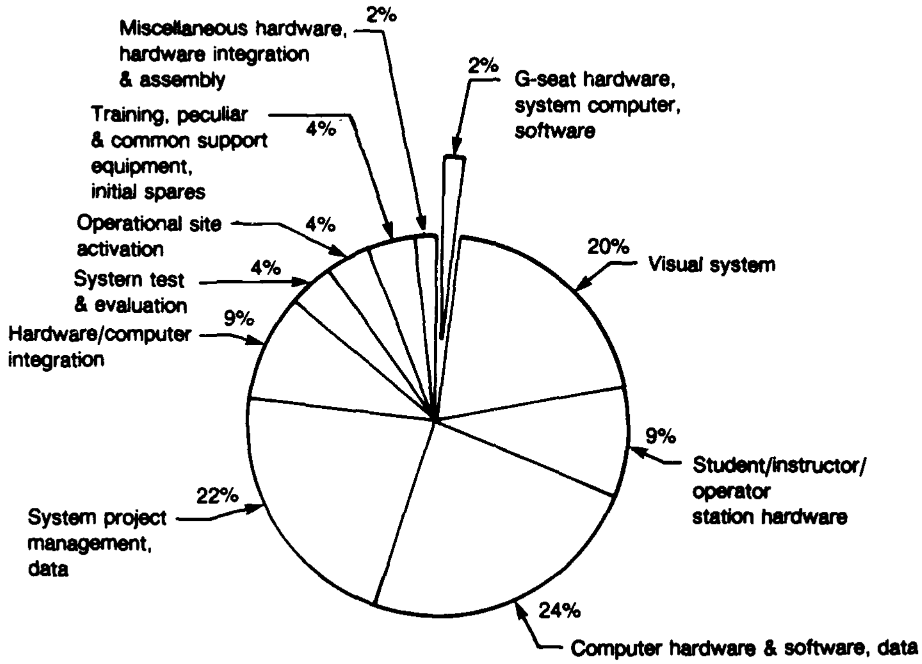

Fig. I.2 -- Cost distribution for prototype: G-seat alternative

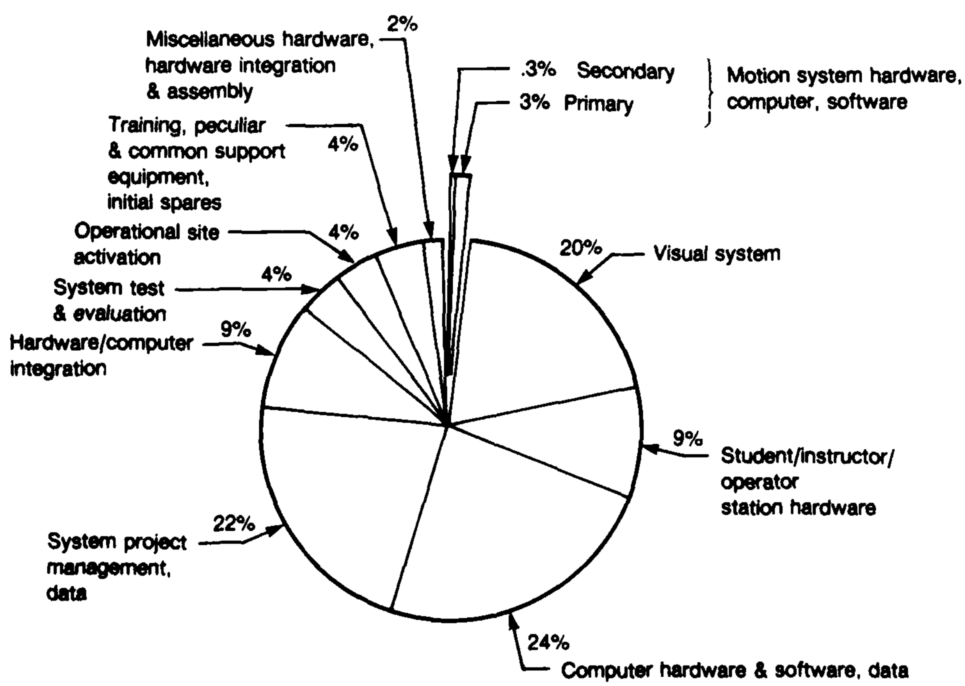

Fig. I.3 -- Cost distribution for prototype: Motion platform alternative

Table I.3

WBS ELEMENTS INCLUDED IN COST CATEGORIES

Cost Category	WBS Elements
Student/instructor/operator station hardware	1.1.2 1.1.3
Computer hardware & software, data	1.1.4 1.1.9 1.1.10 1.1.11 1.1.12 1.1.16
Visual system	1.1.5 1.1.13
Motion system hardware, computer, software	1.1.6 1.1.14
G-seat hardware, computer, software	1.1.7 1.1.15
Hardware/computer integration	1.1.17
Miscellaneous hardware, hardware integration & assembly	1.1.1 1.1.8
Training, peculiar & common support equipment, initial spares	1.2 1.4 1.9 1.11
System project management, data	1.6 1.7
Operational site activation	1.8
System test & evaluation	1.5

As Figs. I.1, I.2, and I.3 display, the major contributors to the prototype's cost are computer hardware and software, and data; system project management, and data; and the visual system. A large percentage

of the computer software and data costs are nonrecurring. The incremental cost for adding g-seat capability is 2 percent of the total development cost. When the prototype includes a motion platform, the primary costs--motion system hardware, computer/software, etc.--incrementally increase development cost about 3 percent, with secondary costs--additional costs to the other systems due to the presence of the motion platform--adding about three-tenths of 1 percent. The total incremental cost of adding the motion platform to the prototype system is about 3.3 percent.

Costs of Production Units. Figures I.4, I.5, and I.6 show the distribution of costs for the production units. Since much of the software and data costs are incurred during the prototype phase, the cost distribution for the production units looks quite different. The visual system dominates the production costs, accounting for 40 percent

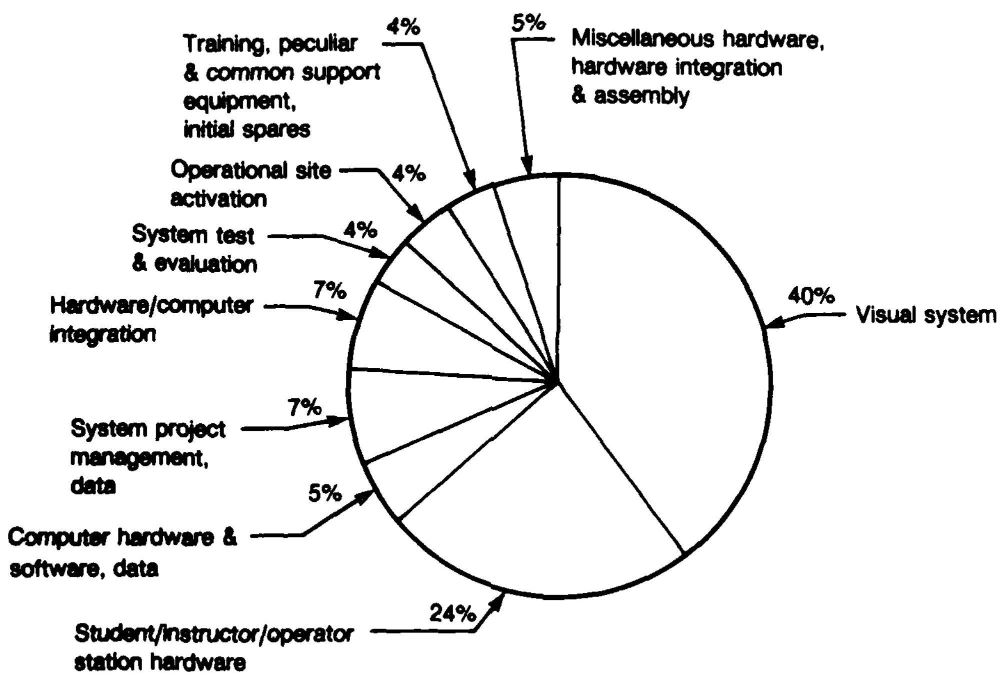

Fig. I.4 -- Cost distribution for production units: No-motion alternative (Average unit production price)

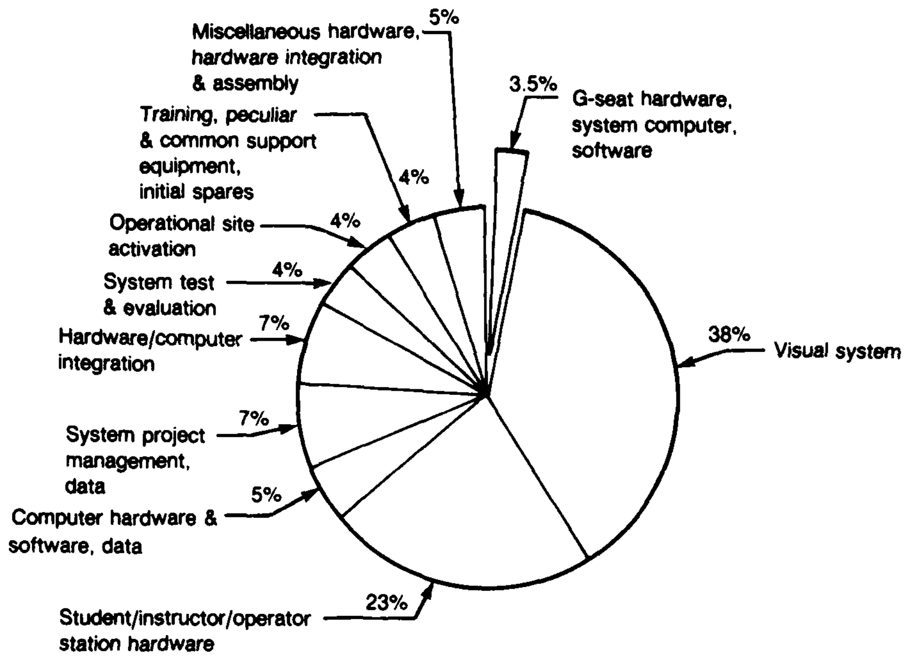

Fig. I.5 -- Cost distribution for production units: G-seat alternative (Average unit production price)

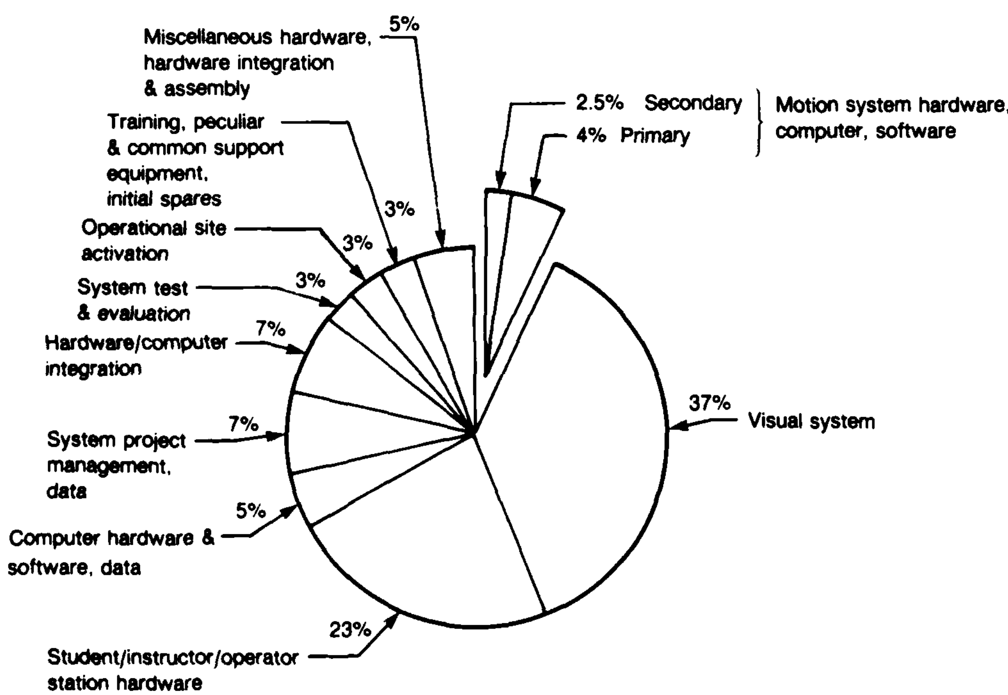

Fig. I.6 -- Cost distribution for production units: Motion platform alternative (Average unit production price)

of the total. The student/instructor/operator station hardware is the next largest cost contributor, accounting for about one-quarter of the total costs. The remaining cost elements each contribute less than 10 percent.

For the simulator with g-seat motion, the inclusion of two g-seats accounts for only 3.5 percent of the system's production cost (see Fig. I.5). Inclusion of a motion platform accounts for only 6.5 percent of the six-dof system's production cost (see Fig. I.6). Four percent are costs directly related to the motion platform, with the remaining 2.5 percent being secondary costs--costs incurred by other systems due to the presence of the motion platform. Figure I.7 displays the contribution of the individual motion system components to that system's cost.

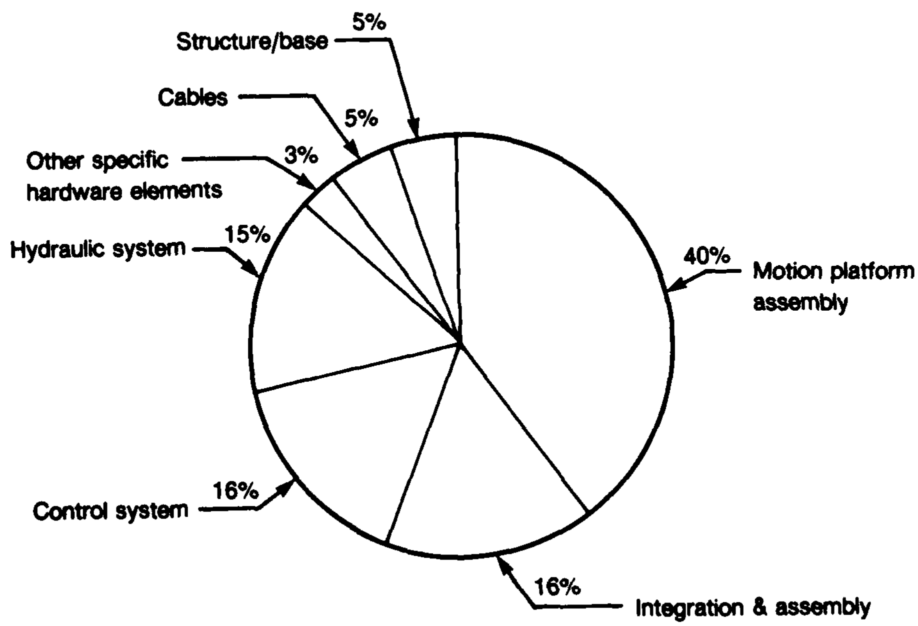

Fig. I.7 -- Cost distribution for the six-dof motion platform system

Figure I.8 displays the total program acquisition (prototype and procurement) cost distribution for the simulator with a motion platform. Again at the program level, visual system costs dominate, followed by the student, instructor and operator station hardware. The motion platform contributes less than 6 percent of the program acquisition costs.

Table I.4 shows program acquisition costs for the seven production simulator systems.

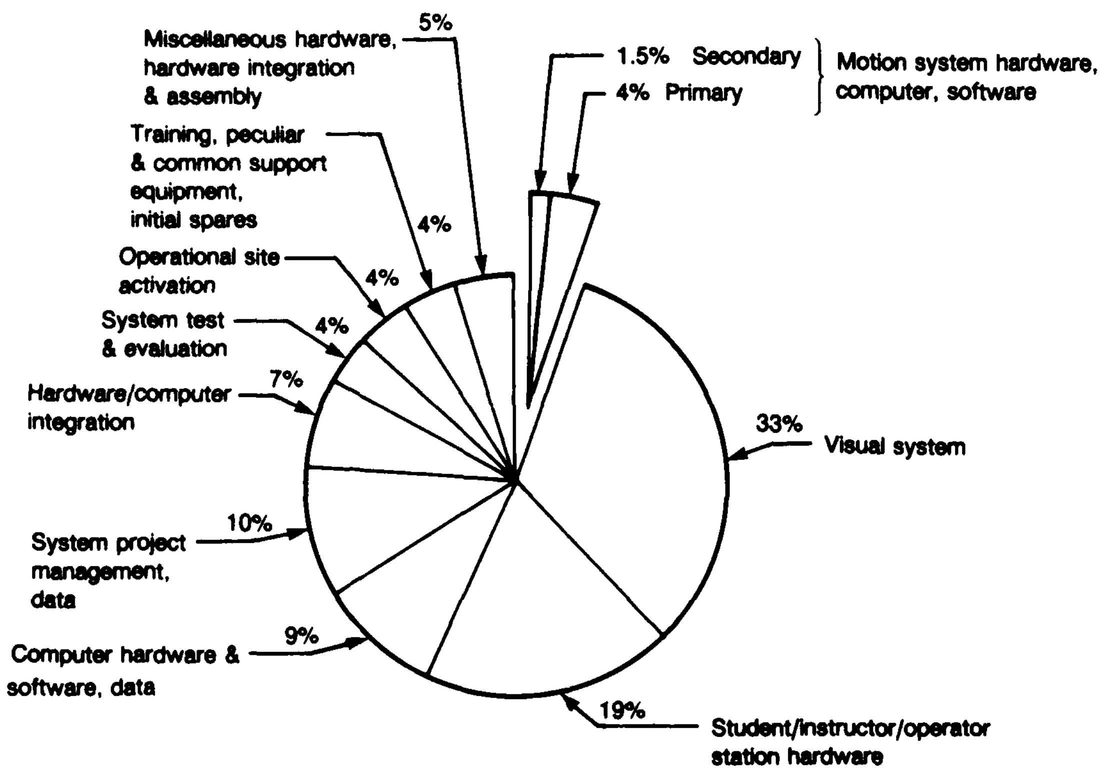

Fig. I.8 -- Cost distribution for program acquisition: Motion platform alternative (Program includes one prototype and seven production simulators)

Table I.4

PROGRAM ACQUISITION COST
(Millions of FY85 dollars)

Alternative	Prototype Cost	Average Production Unit Cost (7 Needed)	Total Program Acquisition Cost
No motion	28.12	13.25	120.9
G-seat	28.55	13.74	124.7
Motion platform	28.90	14.11	127.7

Facilities Costs

Table I.5 shows the disposition of simulators at the Strategic Airlift Training Center (Altus) and at the five MAC operational bases presently supporting the C-141 fleet. Training facilities are being upgraded at Altus as new simulators are introduced, replacing buildings that have been in service from 15 to 20 years and which no longer meet

Table I.5

DISTRIBUTION OF FLIGHT SIMULATORS

Location	Squadrons	Simulators
Training Center Altus OK	(Training center)	3
Operational Bases		
Charleston WV	3	1
McChord WA	2	1
McGuire NJ	3	1
Norton CA	3	1
Travis CA	2	1
Total	13	8

present environmental regulations, fire codes, and noise restrictions. The C-5 training devices at Altus are being enhanced to accommodate simulators with a six-dof capability, and new facilities are under construction to house them. In the process, the C-141 simulator bays also are being replaced and, although the C-141 simulators are limited to three-dof motion, the bays are being increased to accommodate the larger six-dof devices in anticipation of future requirements. (It was actually less costly to construct the adjacent bays with the same roof height than to step them down to the minimum height dictated by the three-dof C-141 devices). Since no plans are in process to replace the training facilities at the five operational C-141 bases, we assumed that the introduction of new C-17 flight simulators would signal the need for new facilities at those locations regardless of whether fixed platform or six-dof simulators are selected for the new aircraft.

When we began this research, we expected training facility costs to be an important consideration in the motion platform cost/benefit equation. Obviously, a flight simulator with six-dof motion requires considerably more floor space than one that is fixed to the floor. A motion platform also requires a thick (12 in vs. 6 in) steel-reinforced concrete pad to support the heavy equipment, a high roof, trenches for its hydraulic plumbing, more air conditioning and electrical power, and a larger hydraulic pump room, isolated to contain the noise it creates. As it turned out, the simulator bay is a relatively small part of the overall training facility (see Table I.6 for a breakdown of the space requirements) and the added construction cost dictated by the six-dof device is not excessive, particularly in the context of a 25-year LCC.

Table I.7 compares the costs of a training facility sized for either a fixed (no-motion) platform or a six-dof flight simulator.[6] (The facility requirements for the g-seat case are assumed to be approximately the same as those of the no-motion case.) As expected, the costs of the flight simulator bay and associated air conditioning,

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[6]We are indebted to the Engineering Directorate at MAC Headquarters, particularly Mr. Charles Fields, for these estimates. Jan Leendertse, a licensed civil engineer on the Rand staff, verified the completeness and reasonableness of the MAC estimates.

Table I.6

FLIGHT SIMULATOR FACILITY SPACE ALLOCATION
(Square feet)

Purpose	No-Motion Case	Six-dof Motion Platform Case
Flight simulator bay	1,024	1,936
Hydraulic pump room	80	190
CPT bay	1,050	1,050
PTT bay	400	400
Computer room	1,230	1,230
Mechanical room	320	320
Telephone/electronics room	100	100
Briefing rooms	840	840
Group briefing room	270	270
Maintenance supervisor's office	180	180
Maintenance shop	490	490
Maintenance locker room	100	100
Break area	170	170
OIC/NCOIC office	200	200
Operations office	320	320
Instructors' office	600	600
Restrooms, janitor	300	300
Computerized learning center	600	600
Other	1,704	1,704
Total	9,978	11,000

NOTE: The six-dof motion platform case accommodates a six-dof motion platform and associated equipment.

etc., are proportionally higher for the motion platform case; however, those costs are dwarfed by the basic facility requirements that are the same for both types. The bottom line of Table I.7 indicates the total estimated cost of replacing the present C-141 training facilities at the five MAC operational bases shown earlier in Table I.5. The new facilities at Altus will be adequate for the three training center simulators. At $7,150,000 the six-dof facility requirements exceed the cost of the fixed platform requirements by only 10 percent.

Table I.7

ESTIMATED COST OF NEW FLIGHT SIMULATOR TRAINING FACILITIES
(FY85 dollars)

Facility	No-Motion Case	Six-dof Motion Platform Case	Increase
Flight simulator bay[a]			
Roof	5,837	11,035	5,198
Walls	21,486	67,528	46,042
Floor	2,560	4,840	2,280
Floor reinforcement	0	1,613	1,613
Foundation	5,666	7,790	2,124
Bay subtotal	35,549	92,806	57,257
Hydraulic pump room	6,400	15,200	8,800
Electrical	27,000	36,000	9,000
Illumination	2,240	4,827	2,587
Air conditioning	10,500	46,500	36,000
Cooling water	15,000	33,000	18,000
Other[b]	22,000	22,000	0
Total simulator area	118,689	250,333	131,644
(Rounded)	119,000	250,000	132,000
Other training facilities	1,180,000	1,180,000	0
Grand total per base	1,299,000	1,430,000	131,000
Total, 5 bases[c]	6,495,000	7,150,000	655,000

[a]Dimensions (ft):

	Length	Width	Height
Fixed base	32	32	14
Six-dof	44	44	32

[b]Common equipment such as bridge crane, fire alarm and Halon fire extinguishing systems, heating systems, communications, etc.

[c]Training facilities at Altus are adequate to house the C-17 simulators.

It might be argued that in a time of fiscal austerity it would be feasible to house fixed platform simulators in existing training buildings whereas new construction could not be avoided for the six-

dof devices. Judging by the above cost estimates, it would appear that the new simulator bays could be constructed for about $250,000 each, although an additional sum would be needed to remodel and provide an interface with the existing facilities. However, the effect of these one-time costs on the comparison of the total 25-year costs of the no motion and six-dof motion platform cases would not be pronounced. Moreover, it seems unlikely that the old facilities can withstand another 25 years without replacement, so the total construction costs probably would only be delayed rather than avoided.

Operating and Support Costs

To assess O&S costs, we compared costs for six-dof simulators with those for fixed platform simulators. Time constraints did not permit a detailed investigation of the O&S costs of g-seats, but some information received from a Navy source suggested that two g-seats could cost almost as much to support as a motion platform. G-seats are quite complex in design and the materials from which they are fabricated are subject to considerable wear during use. As their benefits vis-a-vis the motion platform do not make g-seats strong contenders in the transport aircraft simulator application, we approximated the g-seat system's probable O&S costs by simply scaling the motion platform's O&S costs by the ratio of their acquisition costs, i.e., the g-seat simulator acquisition costs are 97.5 percent as much as the cost of the six-dof motion platform system. We assumed that their O&S costs would scale approximately with this percentage relationship.

Table I.8 compares the average annual O&S costs of fixed platform simulators with those mounted on six-dof full motion platforms. The "Increase" column displays the marginal cost of the motion platforms. Separate estimates are derived for a typical operational base having a single flight simulator, and for an aircrew training center (Altus) with three simulators in a single facility. These estimates are followed by system totals that combine the simulator costs of five operational bases and one training center. Finally, the average annual totals are converted to 25-year life cycle O&S costs.

Table I.8

SIMULATOR OPERATING AND SUPPORT COSTS
(In thousands of FY85 dollars)

Cost Element by Base	Number of Simulators	No-Motion Case	Six-dof Motion Platform Case	Increase
ANNUAL O&S COSTS				
OPERATIONAL BASE	1			
Personnel		1,987	2,019	32
Depot maintenance		9	10	1
Maintenance material		45	50	5
Utilities		45	65	20
Modifications/software updates		375	400	25
Supplies and other		15	15	--
Total		2,476	2,559	83
TRAINING BASE	3			
Personnel		4,397	4,493	96
Utilities		116	176	60
Other		1,333	1,426	93
Total		5,846	6,095	249
SYSTEM TOTAL ANNUAL O&S	8	18,226	18,890	664
25-YEAR O&S COST	8	455,650	472,250	16,600

NOTE: System total = training base + 5 operating bases.

Our estimates confirm the widely held belief that motion platforms are not a significant contributor to the costs of operating flight simulators: Their use increases O&S costs by about 4 percent. Better design, noise isolation, and the use of low-pressure hydraulic systems also have dramatically reduced the downtime, high decibel readings, and hazards attributed to past generations of motion platforms.

We experienced difficulty in finding documentation to verify the anecdotes and assertions regarding the high reliability and durability of motion platforms. This very difficulty in acquiring data may in itself be a form of verification for their alleged low operating cost. Normally, Air Force cost analysts tend to focus on the important costs, being content to "factor in" the elements that have little influence on the outcome of their studies. Unfortunately for the motion platform study, much of the cost data we sought was of the type that qualified for the "other costs" factor treatment. Personnel costs predominate, however, accounting for about 80 percent of the total O&S costs, and we have a good grasp of the manning requirements of MAC simulators.

Personnel Requirements. Our personnel estimates are limited to the requirements of the specified flight simulators. This manning is assumed to be a part of, and marginal to, the requirements of existing aircrew training organizations. Although the Air Force is moving toward a contractor-operated aircrew training approach, our data base was limited to the ongoing military training operation, and our personnel estimates therefore reflect the military form of training operation. This implies relatively high turnover rates, with additional apprentice-level manpower in the units and extensive on-the-job training programs. Moreover, the policy of moving military personnel from base to base over the course of their careers also adds to the units' retraining needs. The around-the-clock operation that characterizes simulator use and maintenance requires about four people per slot, a figure that allows for squadron duty, sick leave, vacations, and other non-productive time.

We based our manning estimates on data provided by MAC Headquarters. The manning requirements for C-130 and C-141 flight simulators are shown in Table I.9, covering both the training centers and operational bases. The numbers of instructors in our estimates were based on the C-141 program. However, the C-141 flight simulator does not have a six-dof platform and, for that reason, we based our manning of the maintenance function on the C-130 program. Four additional people were added to provide support for the visual display package (which presently is the responsibility of General Electric). Table I.10 shows our personnel estimates.

Table I.9

DIRECT PERSONNEL REQUIREMENTS OF MAC C-130 AND C-141
FLIGHT SIMULATORS, BY LOCATION

		Authorized Personnel Strength								
	Number of	Instructors			Maintenance			Total		
Base	Simulators	Officer	Enlisted	Civilian	Officer	Enlisted	Civilian	Officer	Enlisted	Civilian
C-130										
Clark	1	10	5	0	0	17	0	10	22	0
Dyess	1	13	6	0	0	13	4	13	19	4
Kirtland	1	12	6	0	0	12	4	12	18	4
McChord	1	13	6	0	0	15	3	13	21	3
Pope	2	17	8	0	0	25	4	17	33	4
Little Rock	4	22	28	2	0	41	22	22	69	24
C-141										
Charleston	1	8	8	0	0	15	6	8	23	6
McChord	1	4[a]	7	0	0	13	7	4	20	7
McGuire	1	9	7	0	0	18	7	9	25	7
Norton	1	10	9	0	0	18	7	10	27	7
Travis	1	8	7	0	0	22	0	8	29	0
Altus	3	19	8	0	0	22	14	19	30	14

[a]9 assigned.

SOURCES: MAC Headquarters, DCS Operations, Directorate of Aircrew Training, Operational Systems Director (DOTS); DCS Logistics, Directorate of Maintenance Engineering, Avionics Systems Division (LGMA); DCS Comptroller, Directorate of Cost and Management Analysis, Cost and Economic Analysis Division (ACMC).

No job slots are specifically allocated to motion platform maintenance by the Air Force. The maintenance staffs are cross-trained and capable of handling all jobs affecting the operation of the training facility, including the few tasks attributable to the motion platform: inspections, changing seals, etc. We added one man-equivalent for the six-dof simulators to reflect an expected increase in workload and additional time spent per task because of the reduced accessibility of the elevated work platform, the need to climb up and down ladders to get parts and tools, and because two individuals may be required for some

Table I.10

FLIGHT SIMULATOR PERSONNEL ESTIMATE

Personnel by Base Type	Number of Simu-lators	Officer	Enlisted	Civilian	Total
OPERATIONAL BASE	1				
Instructors		9	8	0	17
Maintenance		0	18	4	22
Total direct		9	26	4	39
Support		0	4	1	5
Total personnel		9	30	5	44
TRAINING BASE	3				
Instructors		19	8	0	27
Maintenance		0	46	18	64
Total direct		19	54	18	91
Support		1	5	3	9
Total personnel		20	59	21	100
Total system	8	65	209	46	320

NOTE: Total system = training base + 5 operational bases.

jobs which, on the ground, could be accomplished with a single worker. The jostling of electronic components by the moving platform is not believed to be a significant problem because their design takes the environment into consideration.

The flight simulator career fields are being phased out by the Air Force both because of the need for these scarce military personnel in allied occupational fields and because it generally is believed that simulator training and maintenance are the kinds of non-combat functions that can be performed better and cheaper by civilian contractors. A personnel reduction of between one-third and one-half is anticipated because of the generally higher average skill level of the civilian employees and the more stable work force. This suggests that our personnel cost estimates are on the high side for a future simulator system that may be operated by a contractor.

Personnel Costs. After estimating the needed manpower, we calculated their annual costs by means of the cost factors shown in Table I.11. The relatively high cost of the military personnel results

Table I.11

ANNUAL PER CAPITA COST FACTORS (CONUS)
FOR USAF ACTIVE DUTY PERSONNEL
(FY85 dollars)

	Officer			Enlisted		
	Rated					
Cost Element	Pilot	Other	Other	Aircrew	Other	Civilian (MAC)
ACQUISITION AND TRAINING						
Acquisition	39,350	39,350	39,350	2,800	2,800	
Training (ATC)	288,110[a]	56,670[a]	9,110	3,810[a]	7,700	
Total	327,460	96,020	48,460	6,610	10,500	
Annual turnover rate	.115	.102	.076	.164	.164	
AVERAGE ANNUAL COST						
Pro rata acquisition and training	37,658	9,794	3,683	1,084	1,722	
Pay and Allowances[b]	57,100	57,100	53,330	25,470	24,030	24,130[c]
PCS Travel[d]	1,220	1,220	1,220	460	460	
BOS Nonpay[d]	4,950	4,950	4,950	4,950	4,950	4,950
Medical O&M[d]	790	790	790	790	790	
Total	101,718	73,854	63,973	32,754	31,952	29,080
Rounded	101,720	73,850	63,970	32,750	31,950	29,080

SOURCE: AFR 173-13 (Feb. 1984 revision). Tables 3-1, 3-5, 3-7, 3-10; CORE model factors, Fig. 7-1. Cost factors in source document were in FY85 dollars unless otherwise noted below.

[a]Excludes training conducted by the major commands. FY84 factors inflated 4.5 percent for aircrew training; 4.2 percent for other training.

[b]Includes imputed retirement annuity--51 percent of base pay--and 5 percent pay raise.

[c]Civilian pay includes the government retirement contribution of 7 percent. The civilians contribute another 7 percent toward their own retirement fund.

[d]FY84 factors inflated 4.2 percent.

from the large proportion of instructor pilots in the organization and inclusion of the future retirement liability, presently estimated as 51 percent of military base pay.

Logistics Support. Ogden Air Logistics Center, at Hill AFB, has the primary responsibility for flight simulator logistics support. At our request, the Ogden staff prepared a computer tabulation of the unscheduled maintenance manhours and shop manhours for six-dof flight simulators. Data from the undergraduate pilot training (UPT) program were selected for the example because its six-dof simulators were believed to reflect long-run maintenance experience better than the relatively new C-130 simulators. The latter more closely approximate a heavy transport type of simulator, but they have not yet had enough use to establish a reliable maintenance and material demand history.

Table I.12 presents the UPT maintenance manhour distribution by major WBS category, with the motion platform elements grouped at the top. As is evident from the table, the motion platform only accounted for 3 percent of the unscheduled maintenance manhour total. In the case of shop maintenance, the motion platform accounted for 1 percent.

Maintenance Material. Deriving the cost of motion platform maintenance material proved very difficult and time-consuming at Ogden, involving the use of two sequential sets of microfiches to obtain the cost of each individual item. A scan of the data by an experienced staff member indicated that the motion platform items tended to be inexpensive--seals, packing material, and small hardware items. In view of the light maintenance activity on motion platforms evidenced in Table I.12 and the low unit costs of the material involved, we decided to use an estimate offered by the contractors presently supporting Air Force simulator training--$5,000 per simulator per year. For the total simulator, we used an estimate given in the recent MAC/ACMC study of flight simulator costs at MAC Headquarters (Martin, 1984).

Depot Maintenance. The cost of depot maintenance support for simulator motion platforms was estimated on the basis of UPT experience. Data extracted from the X21 Report for FY85 projected total motion platform depot maintenance costs at $53,120. As shown in Table I.13, we adjusted this figure upward to account for a significantly larger repair

Table I.12

DISTRIBUTION OF FY84 BASE LEVEL MAINTENANCE MANHOURS
ON 44 T50 (T-39 AIRCRAFT) FLIGHT SIMULATORS

Work Unit Code	Description	Unscheduled Maintenance Manhours				Shop Maintenance Manhours			
		Oct-March	April-Sept	Total	% of Total	Oct-March	April-Sept	Total	% of Total
	MOTION PLATFORM								
DWE	Motion platform	184	265	449		2	2	4	
DWU	Motion cabinet	72	77	149		29	3	32	
DWW	Hydraulic pump	196	165	361		2	0	2	
DWX	Hydraulic pump (hoses)	11	5	16		6	0	6	
	Total motion platform	463	512	975	3	39	5	44	1
	OTHER								
DWA	Cockpit	8,428	4,360	12,788		161	179	340	
DWB	Control loading	215	124	339		19	3	22	
DWC	Cockpit cabinet	441	2,382	2,823		2,532	400	2,932	
DWD	Console operator station	83	94	177		58	43	101	
DWF	CPU#1	168	80	248		48	12	60	
DWG	CPU#2	2,060	66	2,126		29	3	32	
DWH	MPC cabinet	2,141	76	2,217		25	22	47	
DWJ	CPU#3	39	91	130		6	19	25	
DWK	Equipment stand	40	41	81		0	6	6	
DWL	Computer power junction box #1	0	4	4		0	0	0	
DWM	Power cabinet	38	8	46		0	0	0	
DWN	Magnetic tape cabinet	12	2	14		1	0	1	
DWP	Disk unit	21	53	74		0	2	2	
DWQ	Disk unit	14	33	47		4	1	5	
DWV	Computer power junction box #2	0	2	2		0	0	0	
DWY	Air compressor	4	2	6		0	0	0	
DWZ	Decimal readout unit	0	1	1		0	0	0	
DW1	Products of combustion monitor #1	9	20	29		0	0	0	
DW2	POC monitor #2	1	0	1		0			
DW3	Boarding ramp	55	2,031	2,086		0	3	3	
DW4	Visual interface cabinet	2	17	19		13	35	48	
---	Not elsewhere classified	2,117	2,586	4,703		16	49	65	
	Total other	15,888	12,073	27,961	97	2,912	777	3,689	99
	Grand total	16,351	12,585	28,936	100	2,951	782	3,733	100

SOURCE: Maintenance Actions, Manhours, and Aborts by Work Unit Code, 1984.

Table I.13

ANNUAL COST OF SIX-DOF SIMULATOR
DEPOT-LEVEL MAINTENANCE SUPPORT
(FY85 dollars)

Item by Repair Location	Total Simulator	Motion Platform
Ogden ALC		
88 UPT simulators[a]	740,881	43,436
Adjusted (Valve)[b]	9,684	9,684
Adjusted (Actuator)[c]	63,000	63,000
Adjusted total	813,565	116,120
Average per simulator	9,245	1,320
Warner Robins ALC		
44 UPT simulators[a]	53,000	--
Average per simulator	1,205	--
Total per simulator	10,450	1,320

[a]X-21 form.

[b]Adjustment to reflect an expected increase in a valve repair rate in subsequent years.

[c]Adjustment based on an assumption that 2/3 of simulator legs will require overhaul over a 10-year period.

action programmed for a costly valve in FY86. Also, in view of the long life-cycle time-span assumed for simulators in our study, we made an assumption that two-thirds of the motion platform actuators (legs) would require an overhaul during a ten-year period.

Although Ogden is the prime Air Logistics Center (ALC) for simulators, computer repairs are managed by the Warner Robins ALC. To complete our calculation of simulator depot maintenance costs, Warner Robins ALC provided us with a tabulation of the cost of depot-level maintenance on UPT simulator computers, which we then added to the Ogden figures in Table I.13. When the Ogden and Warner Robins depot maintenance costs are combined, the motion platform costs are equal to about 13 percent of the total depot costs of the UPT simulator system.

Utility Costs. The utility costs for the motion platform were estimated on the basis of the requirements for C-130 flight simulators, as stated in the "Orange Book,"[7] and the average cost for large industrial users of electricity--5.6 cents per kilowatt hour (*Electric Power Annual 1983*). Actual electricity costs can vary from 1.8 cents per kilowatt hour in the Seattle area to 12 cents in San Diego, but utility costs are not a significant cost element in this study. The MAC/ACMC study (Martin, 1984) is the source of our estimate of utility requirements for the complete simulator.

Modifications and Software Updates. The estimates for simulator modifications and software are highly conjectural. Over a period of 25 years we would expect several software revisions and at least one major refurbishment involving the purchase of new computers. The timing and extent of these actions, however, is difficult to predict because the simulators must compete for funds with the aircraft and, according to simulator managers, training devices do not enjoy the highest priority. Our estimate is based on limited F-4 and C-135 data and represents software updates and improved computers. Very little of this cost element is attributed to the motion platform.

Supplies and Other. This element covers minor equipment, office furnishings, and supplies. The source of this small item is the MAC/ACMC study (Martin, 1984).

Total O&S Cost. When the various O&S costs are summed, we find that the motion platform adds only 4 percent to the amount needed to support a fixed platform simulator.

Total 25-Year LCC for 8 Simulators

No Motion and Six-dof System Cost Totals. Table I.14 presents a summation of the acquisition, facilities, and O&S costs of the alternative fixed platform and six-dof simulator systems over an assumed life cycle of 25 years. To make the system costs more comprehensible, they also are shown as average annual costs. The latter figures

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[7] *USAF Training Equipment Characteristics*, Air Force Guide #4, ASD/AFSC, Wright-Patterson AFB, Addendum #36, January 1981.

Table I.14

FLIGHT SIMULATOR 25-YEAR SYSTEM COSTS
(Thousands of FY85 dollars)

Cost Element	No-Motion Case	Six-dof Motion Platform Case	Increase
Acquisition	120,850	127,670	6,820
Facilities	6,495	7,150	655
25-Year O&S	455,650	472,250	16,600
25-Year System Cost	582,995	607,070	24,075
Average Annual cost	23,320	24,283	963
Ratio	1.00	1.04	.04

NOTE: Altus + 5 operational bases. Training facility at Altus is adequate without modification.

essentially consist of one year's worth of O&S costs plus a pro rata (1/25) share of the acquisition and facilities costs. Although these average annual costs may be easier to grasp, it should not be overlooked that the expenditures on acquisition and facilities must, in fact, be funded up front. Also, the annual costs are averages over time. For the motion systems the depot maintenance and material cost elements would tend to be lower in the beginning years and higher later on as wear and tear take their toll on the moving parts. Besides this trend, the year in which the major refurbishment takes place will register above-average costs.

Table I.14 indicates that adding motion platforms to the flight simulators adds $24 million (about $960,000 per year) to the total system cost. This is 4 percent above the cost of the no-motion case.

G-Seat Cost Totals. For the g-seat case, the summation of total simulator acquisition, facilities, and O&S costs for the 25-year period is $592.6 million, or $23.7 million for the comparable average annual cost. The g-seats (two per simulator) add about 2 percent to the cost of the no-motion case. The incremental acquisition cost of the g-seats for eight simulators is $3.88 million and the incremental 25-year O&S costs amount to $5.75 million. As the facility requirements of the no-motion case are adequate for the g-seat alternative, the total add-on costs sum to $9.63 million (about $385,000 per year).

SENSITIVITY ANALYSES

For each simulator alternative considered, the preceding cost analysis assumed the same number of simulators (eight), the same utilization (80 hours per week), and the same peacetime aircraft usage (3.2 hours per day).[8] To test the sensitivity of our cost results to these assumptions, we conducted two sensitivity analyses:

1. We investigated the influence on costs of changes in simulator utilization and procurement that might arise from the substantial differences in potential training capability of the three alternatives (see Appendix F).
2. To examine possible economies of scale, we computed the change in costs caused by doubling the simulator procurement from eight to sixteen. This might occur in the event that the more demanding nature of the C-17 mission and the higher C-17 crew ratio lead to a greater demand for simulator training than is currently satisfied by eight simulators for C-141 strategic airlift crews.

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[8]Until now, our discussion of cost has considered only simulator costs for training; we neglected aircraft costs for training because they were constant for different simulator alternatives. However, the discussion of cost in our first sensitivity analysis will consider "training costs," which include aircraft as well as simulator costs to reflect their tradeoffs.

How Variations in Training Capability Could Influence Costs

If one simulator has less training capability than another, it might be used less or procured in smaller quantities because the operator finds it less useful for training.[9] In such a situation, the operator would strive to shift some training to the aircraft,[10] although--as we have indicated--certain tasks cannot be shifted to the aircraft for reasons of prudence or difficulty. Such a reduction in simulator utilization or procurement and the associated increase in aircraft utilization could obviously influence the training cost differences among simulator alternatives.

Although we lack sufficient information to estimate how demand for a C-17 simulator might change with training capability, we can parametrically estimate how costs would change if some training shifted from the simulator to the aircraft. The smaller the training capability of an alternative, the larger the need for this shift. (As Appendix F indicated, the no-motion alternative can train only 18 percent of the training tasks and task variations and the g-seat alternative only 35 percent; however, the motion platform can train 100 percent.) Such shifting drives up training costs of the lower-capability alternatives because aircraft marginal operating costs are more than eight times those for simulators.[11]

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[9]Alternatively, the Air Force could attempt the same training with less capable motion cueing or it could concentrate on more repetitive training of those tasks the simulator could adequately train. But this would incur some unquantifiable risks from training to a lower standard. Such risks would include the possibility of not having fully trained crews for a wartime contingency and the possibility of losing an $80 million aircraft, its crew, and its cargo in peacetime because the quality and diversity of motion cues experienced by crew members in simulator training did not equip them to respond properly to the cues experienced in an actual in-flight emergency.

[10]KC-10 instructors suggested to us that they would probably move instrument checks back into the aircraft if they did not have a simulator with adequate motion.

[11]Greater aircraft usage for training would also increase aircraft exposure to accidents (see Appendix G).

For the less capable alternatives, the savings from reduced utilization--or even from reduced procurement--are overwhelmed by the added training costs resulting from greater reliance on the aircraft.[12]

To see why this is true, first suppose (unrealistically) that all tasks and task variations can indeed be trained in the aircraft. Figure I.9 shows the decrease in simulator operating costs and the increase in aircraft operating costs as a function of the reduction in simulator hours for two cases, one in which eight no-motion simulators are procured and the other in which the procurement is proportionately reduced as operating hours are reduced. Figure I.10 shows the incremental training costs that result from adding together these additional costs and savings. Even under the extremely optimistic assumption that as much training can be accomplished in one aircraft hour as in one simulator hour, an additional training cost of about $21 million is incurred over 25 years for each 1 percent reduction in simulator training hours that shift to the aircraft. Because of the almost four-to-one dominance of simulator operating costs over procurement costs, the results change only slightly if fewer simulators are procured to reflect hypothetically lower usage. In either case, we conclude that it would be less expensive to pay an extra $24 million for the motion platform alternative[13] than to incur the larger additional aircraft operating costs associated with any shift of slightly more than one percent of simulator hours to the aircraft.

Now suppose (realistically) that some tasks and task variations not trainable in a low-capability simulator cannot be shifted to the aircraft. (This was 48 percent of the tasks and task variations for the

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[12]Because the aircraft force is sized to meet a wartime utilization requirement that is three to four times that planned for peacetime, there would appear to be no justification for buying more aircraft solely for training purposes. Using the aircraft more extensively for training, however, would consume the useful life of the force more quickly, another cost associated with the lower capability motion alternatives.

[13]The $24 million is the system cost differential between the no-motion alternative and the motion platform alternative previously calculated assuming the same utilization and number of simulators (see Table I.14).

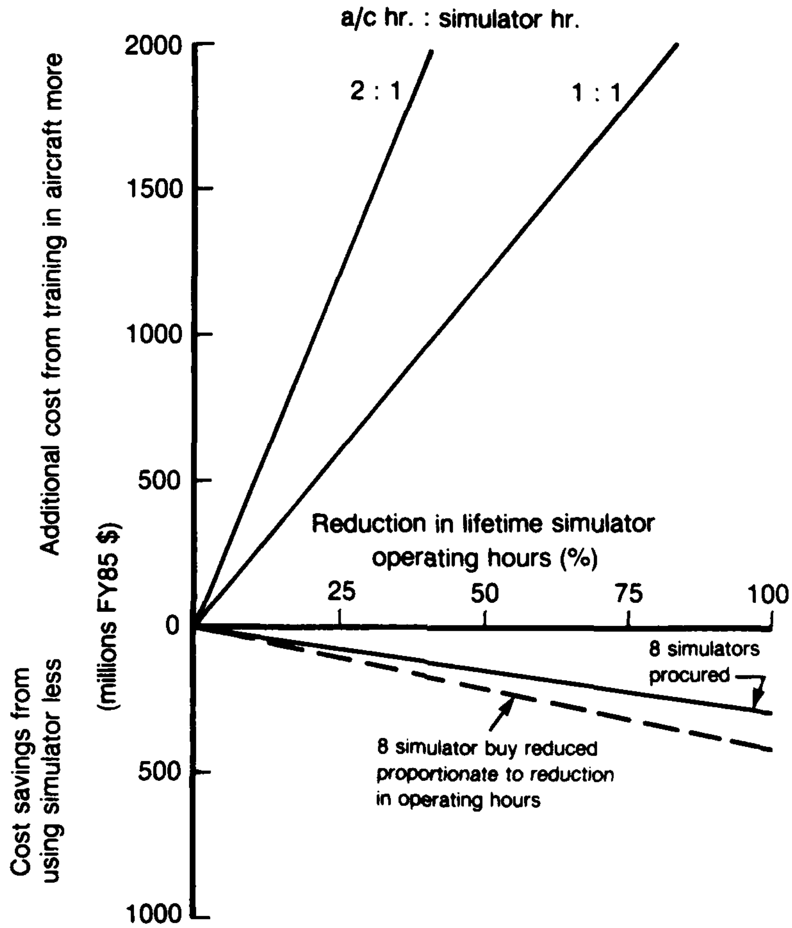

Fig. I.9 -- Costs of using simulator less

no-motion simulator and 40 percent for the g-seat simulator.) While the actual opportunity cost for not training these tasks cannot be estimated here, the lower bound on this cost would correspond to the aircraft's marginal operating cost; the Air Force should be willing to pay that much to train the task in the aircraft (if that were possible) rather than reduce training standards by failing to train the task.

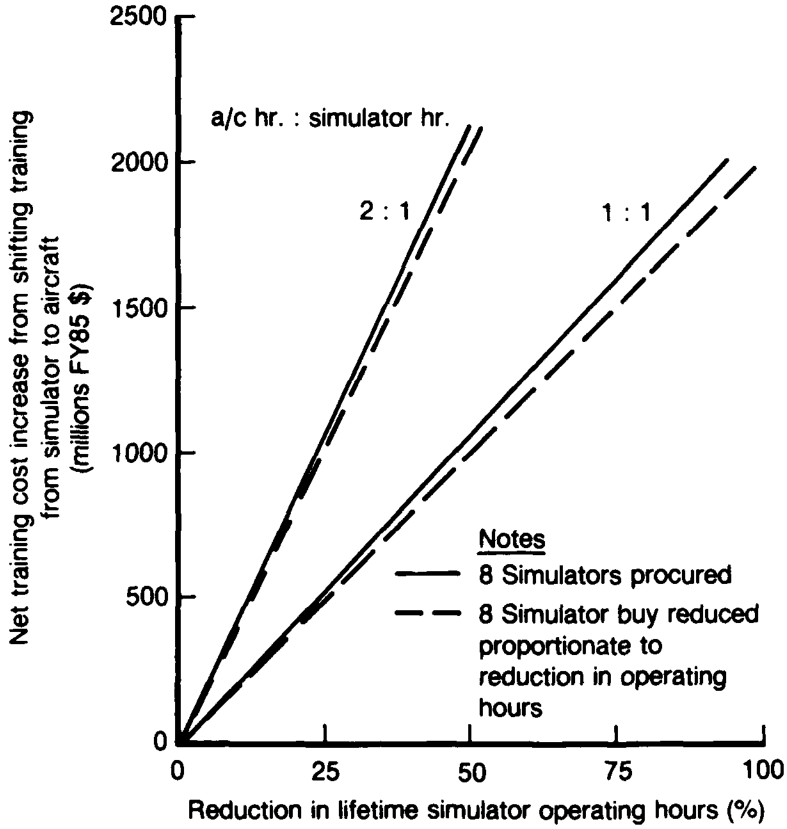

Fig. I.10 -- Additional cost of shifting training from simulator to aircraft

This lower bound on opportunity cost is larger than the corresponding net cost of shifting training to the aircraft (given in Fig. I.10). As more than 40 percent of the tasks and task variations considered cannot be trained at all without the platform motion alternative, this suggests that the extra $24 million for the motion

platform alternative almost certainly would be less expensive than the sum of the operating cost for additional training in the aircraft and the opportunity cost of those tasks that could not be trained.

If more than eight simulators are ultimately needed to satisfy the training demand, this is even more favorable for the motion platform alternative. It can satisfy the additional training demand relatively inexpensively with more simulators, while the lower-capability alternatives incur much larger training costs because of the need to use the aircraft much more. As before, the additional aircraft operating costs and opportunity costs associated with reliance on the lower capability simulator alternatives would dominate the additional acquisition and operating costs of the more capable motion platform alternative.

These results suggest that changes in our assumptions concerning the utilization and number of simulators only serve to enhance the attractiveness of the motion platform alternative.

How Buying Twice as Many Simulators Could Influence Costs

To test for economies of scale, we recalculated system costs assuming twice the number of simulators: two for each of the five operational bases and six for the Altus training center.

No Motion and Six-dof Costs. For the acquisition cost estimates, we added eight more simulators to our original estimates at the production unit cost, i.e., a total of one prototype plus 15 production models. Table I.15 shows the effect on facility costs. The flight simulator bays and auxiliary areas of the training structures at operational bases were assumed to require about 90 percent more space. However, the number of trainees would not be changed so the rest of the facility was increased only 10 percent, reflecting added space in maintenance shops and other rooms related to the somewhat larger maintenance staff. The existing training facility at Altus would have to be enlarged to make room for the three additional simulators and their auxiliary requirements. This was estimated at $333,000 for the no-motion case and $700,000 for the six-dof case. These figures include an allowance for the necessary remodeling of the original training facility to accommodate the addition structure.

Table I.15

ESTIMATED COST OF NEW TRAINING FACILITIES
FOR 16 FLIGHT SIMULATORS
(FY85 dollars)

Facilities by Base Type	No-Motion Case	Six-dof Motion Platform Case	Increase
OPERATIONAL BASES			
Simulator area (basic case)	119,000	250,000	131,000
Add-on (for second simulator)	107,000	225,000	118,000
Other training facilities (basic)	1,180,000	1,180,000	0
Add-on (for second simulator)	118,000	118,000	0
Total per base	1,524,000	1,773,000	249,000
Total for 5 bases	7,620,000	8,865,000	1,245,000
TRAINING BASE			
Modification (3 more simulators)	333,000	700,000	367,000
Total system (16 simulators)	7,953,000	9,565,000	1,612,000

NOTE: Total system = Altus training base + 5 operational bases.

Table I.16 shows the expected personnel strength increases for the 16-simulator alternative. On the basis of an analysis of the instructor and maintenance personnel requirements shown in Table I.9 for MAC bases having varying numbers of simulators, we assumed that the number of pilot instructors would increase about 80 percent whereas the enlisted personnel would increase only 27 percent, as a consequence of economies of scale in the maintenance operation.

A comparison of the O&S costs of the eight-simulator example displayed in Table I.8 with the costs of the 16-simulator example displayed in Table I.17 reveals that the above personnel augmentation adds only 53 percent to the personnel costs of the simulator systems. To account for expected economies of scale resulting from a doubling of the number of simulators, we increased utility costs by 90 percent for the motion platform-related requirements and only 60 percent for the remainder. However, it seemed logical to double the rest of the O&S

Table I.16

PERSONNEL REQUIREMENTS FOR 16 FLIGHT SIMULATORS

Personnel by Base Type	Number of Simu-lators	Officer	Enlisted	Civilian	Total
OPERATIONAL BASE	2				
Instructors		16	8	0	24
Maintenance		0	25	4	29
Total direct		16	33	4	53
Support		0	5	1	6
Total personnel		16	38	5	59
TRAINING BASE	6				
Instructors		38	8	0	46
Maintenance		0	66	26	92
Total direct		38	74	26	138
Support		1	8	5	14
Total personnel		39	82	31	152
Total system	16	119	272	56	447

NOTE: Total system = Altus training base + 5 operational bases.

costs. Overall, the motion platform-related O&S costs increased 74 percent. The total O&S costs of both the no-motion and the six-dof motion platform cases increased 63 percent.

Total 25-year Life-Cycle Cost for 16 Simulators. Table I.18 summarizes the 25-year system costs for 16 simulators. The addition of eight more simulators raised the total marginal costs of the motion platforms by about 85 percent above the eight-simulator system. However, for the simulator systems as a whole, certain elements--particularly personnel--exhibited such pronounced economies of scale that the costs of the 16-simulator systems rose only 68 percent above those of the eight-simulator systems. The cost of the six-dof system with 16 simulators exceeds the cost of the no-motion system by 5 percent rather than the 4 percent noted in the eight-simulator example.

Table I.17

OPERATING AND SUPPORT COSTS FOR 16 SIMULATORS
(In thousands of FY85 dollars)

Cost Element	No-Motion Case	Six-dof Motion Platform Case	Increase
ANNUAL O&S COSTS			
Personnel	22,028	22,385	357
Maintenance material	720	800	80
Depot maintenance	144	160	16
Utilities	540	844	304
Modifications/software updates	6,000	6,400	400
Supplies and other	240	240	--
Total	29,672	30,829	1,157
25-YEAR TOTAL O&S	741,800	770,725	28,925

NOTE: Total = Altus training base + 5 operational bases.

Total 25-year Life Cycle Cost for 16 G-seat Simulators. The acquisition cost of the 16 simulators with g-seats is estimated at \$234.65 million. The facility cost is essentially the same as the no-motion case: \$7.95 million. G-seat O&S costs again were approximated by scaling the O&S costs of the motion platform using the same relationship that was used for the eight-simulator O&S costs, i.e., the g-seat system's O&S costs were assumed to equal 97.5 percent of the motion platform's costs: \$751.84 million. In sum, the 25-year costs of the 16-simulator g-seat case total \$994.44 million, 2 percent above the cost of the no-motion case.

Table I.18

25-YEAR SYSTEM COSTS OF 16 FLIGHT SIMULATORS
(Thousands of FY85 dollars)

Cost Element	No-Motion Case	Six-dof Motion Platform Case	Increase
Acquisition	226,826	240,550	13,724
Facilities	7,953	9,565	1,612
25-Year O&S	741,800	770,725	28,925
25-Year system cost	976,579	1,020,840	44,261
Average annual cost	39,063	40,834	1,770
Ratio	1.00	1.05	.05

NOTE: Altus + 5 operational bases. Training facility at Altus requires modification to house 3 more simulators.

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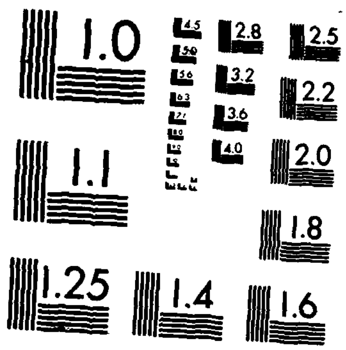

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